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UTILITY PATENT APPLICATION TRANSMITTAL	Atty. Docket No.	X-444-2P-2 US
	First Inventor or Appl. Identifier	Andrew K. Percey
	Title	Digital Spread Spectrum Circuitry
Express Mail Label No.		EL539650663US

APPLICATION ELEMENTS
See MPEP chapter 600 concerning utility patent application contents**ADDRESS TO:** Commissioner for Patents
Box Patent Application
Washington, DC 202311. ☒ *Fee Transmittal Form (e.g., PTO/SB/17)
(Submit an original, and a duplicate for fee processing)2. ☒ Specification [Total Pages **71**]
(preferred arrangement set forth below)

- Descriptive title of the invention
- Cross References to Related Applications
- Statement Regarding Fed sponsored R & D
- Reference to sequent listing, a table, or a computer program listing appendix
- Background of the invention
- Brief Summary of the invention
- Brief Description of the Drawings (if filed)
- Detailed Description
- Claim(s)

6. ☐ CD-ROM or CD-R in duplicate, large table or Computer Program (Appendix)7. ☐ Nucleotide and/or Amino Acid Sequence Submission (if applicable, all necessary)a. ☐ Computer Readable Copy

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c. ☐ Statements verifying identity of above copies3. ☒ Drawing(s) (35 USC 113) [Total Sheets **21**]4. Oath or Declaration [Total Pages **1**]a. ☒ Newly executed (original or copy)b. ☐ Copy from a prior application (37 CFR §1 63(d))
(for continuation/divisional with Box 16 completed)i. ☐ **DELETION OF INVENTOR(S)**
Signed statement attached deleting inventor(s) named in the prior application, see 37 CFR § 1 63(d)(2) and 1 33(b).5. ☐ Application Data Sheet. See 37 CFR 1.76**ACCOMPANYING APPLICATION PARTS**8. ☐ Assignment Papers (cover sheet & document(s))9. ☐ 37 CFR §3.73(b) Statement (when there is an assignee) ☐ Power of Attorney10. ☐ English Translation Document (if applicable)11. ☐ Information Disclosure Statement (IDS)/PTO-1449 ☐ Copies of IDS Citations12. ☐ Preliminary Amendment13. ☒ Return Receipt Postcard (MPEP 503)
(Should be specifically itemized)14. ☐ Certified Copy of Priority Document(s)
(if foreign priority is claimed)15. ☐ Other:16. If a **CONTINUING APPLICATION**, check appropriate box and supply the requisite information below and in a preliminary amendment:☐ Continuation ☐ Divisional ☒ Continuation-in-part (CIP) of prior application No. **09/102,740**Prior application information Examiner **B. Deppe** Group / Art Unit: **2734****For CONTINUATION or DIVISIONAL APPS only:** The entire disclosure of the prior application, from which an oath or declaration is supplied under Box 4b, is considered a part of the disclosure of the accompanying continuation or divisional application and is hereby incorporated by reference. The incorporation can only be relied upon when a portion has been inadvertently omitted from the submitted application parts.**18. CORRESPONDENCE ADDRESS**☒ Customer Number or Bar Code Label**24309**

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2. EXTRA CLAIM FEES

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Multiple Dependent		X	

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Fee Code	Fee (\$)	Fee Description
103	18	Claims in excess of 20
102	80	Independent claims in excess of 3
104	270	Multiple dependent claim, if not paid
109	80	**Reissue independent claims over original patent
110	18	**Reissue claims in excess of 20 and over original patent

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FEE CALCULATION (continued)

3. ADDITIONAL FEES

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Code	Fee (\$)	Fee Description	Fee Paid
105	130	Surcharge - late filing fee or oath	
127	50	Surcharge - late provisional filing fee or cover sheet.	
147	2,520	For filing a request for reexamination	
112	920*	Requesting publication of SIR prior to Examiner action	
113	1,840*	Requesting publication of SIR after Examiner action	
115	110	Extension for reply within first month	
116	390	Extension for reply within second month	
117	890	Extension for reply within third month	
118	1,390	Extension for reply within fourth month	
128	1,890	Extension for reply within fifth month	
119	310	Notice of Appeal	
120	310	Filing a brief in support of an appeal	
121	270	Request for oral hearing	
138	1,510	Petition to institute a public use proceeding	
140	110	Petition to revive - unavoidable	
141	1,240	Petition to revive - unintentional	
142	1,240	Utility issue fee (or reissue)	
122	130	Petitions to the Commissioner	
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126	240	Submission of Information Disclosure Stmt	
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DIGITAL SPREAD SPECTRUM CIRCUITRY

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PRIORITY

This is a continuation-in-part of U.S. Patent
Application Serial No. 09/102,740 filed June 22, 1998.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application relates to commonly assigned,
concurrently filed U.S. Patent Application Serial No.
09/102,704 [docket X-440 US], "Glitchless Delay Line Using
Gray Code Multiplexer", which is incorporated herein by
reference.

FIELD OF THE INVENTION

The present invention relates to delay lock loops (DLLs)
for digital electronics. More specifically, the present
invention relates to DLLs capable of locking clock signals
over a wide frequency range.

BACKGROUND OF THE INVENTION

Synchronous digital systems, including board level
systems and chip level systems, rely on one or more clock
signals to synchronize elements across the system.
Typically, one or more clock signals are distributed across
the system on one or more clock lines. However, due to
various problems such as clock buffer delays, high
capacitance of heavily loaded clock lines, and propagation
delays, the rising edges of a clock signal in different parts
of the system may not be synchronized. The time difference
between a rising (or falling) edge in one part of the system
with the corresponding rising (or falling) edge in another
part of the system is referred to as "clock skew".

1 within logic circuits 190. Skewed clock signal S_CLK is also
2 routed back to delay lock loop 100 on a feedback path 170.
3 Typically, feedback path 170 is dedicated specifically to
4 routing skewed clock signal S_CLK to delay lock loop 110.
5 Therefore, any propagation delay on feedback path 170 is
6 minimal and causes only negligible skewing.

7 Figure 2A provides a timing diagram of reference clock
8 signal REF_CLK, output clock signal O_CLK, and skewed clock
9 signal S_CLK. All three clock signals have the same
10 frequency F (not shown) and period P, and all are active-high
11 (i.e., the rising edge is the active edge). Since output
12 clock signal O_CLK is delayed by propagation delay D, a clock
13 edge 220 of output clock signal O_CLK lags corresponding
14 clock edge 210 of reference clock signal REF_CLK by
15 propagation delay D. Similarly, a clock edge 230 of skewed
16 clock signal S_CLK lags corresponding clock edge 220 of
17 output clock signal O_CLK by a propagation delay SKEW, which
18 is the propagation delay caused by clock skew 180 (Figure 1).
19 Therefore, clock edge 230 of skewed clock signal S_CLK lags
20 clock edge 210 of reference clock signal REF_CLK by a
21 propagation delay DSKEW, which is equal to propagation delay
22 D plus propagation delay SKEW.

23 Delay lock loop 100 controls propagation delay D by
24 controlling delay line 110. However, delay line 110 cannot
25 create negative delay; therefore, clock edge 230 cannot be
26 synchronized to clock edge 210. Fortunately, clock signals
27 are periodic signals. Therefore, delay lock loop 100 can
28 synchronize reference clock signal REF_CLK and skewed clock
29 signal S_CLK by further delaying output clock signal O_CLK
30 such that clock edge 240 of skewed clock signal S_CLK is
31 synchronized with clock edge 210 of reference clock signal
32 REF_CLK. As shown in Figure 2B, propagation delay D is
33 adjusted so that propagation delay DSKEW is equal to period
34 P. Specifically, delay line 110 is tuned so that propagation
35 delay D is increased until propagation delay D equals period
36 P minus propagation delay SKEW. Although propagation delay

1 DSKEW could be increased to any multiple of period P to
2 achieve synchronization, most delay lock loops do not include
3 a delay line capable of creating such a large propagation
4 delay.

5 Phase detector 120 (Figure 1) controls delay line 110 to
6 regulate propagation delay D. The actual control mechanism
7 for delay lock loop 100 can differ. For example, in one
8 version of delay lock loop 100, delay line 110 starts with a
9 propagation delay D equal to minimum propagation delay D_MIN,
10 after power-on or reset. Phase detector 110 then increases
11 propagation delay D until reference clock signal REF_CLK is
12 synchronized with skewed clock signal S_CLK. In another
13 system, delay lock loop 100 starts with a propagation delay D
14 equal to the average of minimum propagation delay D_MIN and
15 maximum propagation delay D_MAX, after power-on or reset.
16 Phase detector 120 then determines whether to increase or
17 decrease (or neither) propagation delay D to synchronize
18 reference clock signal REF_CLK with skewed clock signal
19 S_CLK. For example, phase detector 120 would increase
20 propagation delay D for the clock signals depicted in Figure
21 2A. However, phase detector 120 would decrease propagation
22 delay D for the clock signals depicted in Figure 2C.

23 In Figure 2C, skewed clock signal S_CLK is said to "lag"
24 reference clock signal REF_CLK, because the time between a
25 rising edge of reference clock signal REF_CLK and the next
26 rising edge of skewed clock signal S_CLK is less than the
27 time between a rising edge of skewed clock signal S_CLK and
28 the next rising edge of reference clock signal REF_CLK.
29 However, in Figure 2A, reference clock signal REF_CLK is said
30 to "lag" skewed clock signal S_CLK, because the time between
31 a rising edge of skewed clock signal S_CLK and the next
32 rising edge of reference clock signal REF_CLK is less than
33 the time between a rising edge of reference clock signal
34 REF_CLK and the next rising clock edge of skewed clock signal
35 S_CLK. Alternatively, in Figure 2A skewed clock signal S_CLK
36 could be said to "lead" reference clock signal REF_CLK.

1 After synchronizing reference clock signal REF_CLK and
2 skewed clock signal S_CLK, delay lock loop 100 monitors
3 reference clock signal REF_CLK and skewed clock signal S_CLK
4 and adjusts propagation delay D to maintain synchronization.
5 For example, if propagation delay SKEW increases, perhaps
6 caused by an increase in temperature, delay lock loop 100
7 must decrease propagation delay D to compensate. Conversely,
8 if propagation delay SKEW decreases, perhaps caused by a
9 decrease in temperature, delay lock loop 100 must increase
10 propagation delay D to compensate. The time in which delay
11 lock loop 100 is attempting to first synchronize reference
12 clock signal REF_CLK and skewed clock signal S_CLK, is
13 referred to as lock acquisition. The time in which delay
14 lock loop 100 is attempting to maintain synchronization is
15 referred to as lock maintenance. The value of propagation
16 delay D at the end of lock acquisition, i.e. when
17 synchronization is initially established, is referred to as
18 initial propagation delay ID.

19 However, as explained above, delay line 110 can only
20 provide a propagation delay between a minimum propagation
21 delay D_MIN and a maximum propagation delay D_MAX. During
22 lock maintenance, delay lock loop 100 may lose
23 synchronization if a propagation delay D smaller than minimum
24 propagation delay D_MIN is required to maintain
25 synchronization. Similarly, synchronization may be lost if a
26 propagation delay D greater than maximum propagation delay
27 D_MAX is required to maintain synchronization.

28 For example, if lock acquisition occurs while the system
29 using delay lock loop 100 is at a very high temperature,
30 delay lock loop 100 is likely to achieve synchronization with
31 a very small initial propagation delay ID, since propagation
32 delay SKEW is likely to be large with respect to period P.
33 As the system's temperature increases further, propagation
34 delay SKEW is likely to increase to a point where propagation
35 delay SKEW plus minimum propagation delay D_MIN is greater
36 than period P. In this situation, delay lock loop 100 must

1 undergo lock acquisition again, which may introduce glitches
2 and noise into output clock signal O_CLK, in turn causing
3 glitches and noise in skewed clock signal S_CLK. For
4 critical systems, such glitches are intolerable. Further,
5 for systems designed for operation at multiple clock
6 frequencies, low frequency operation is likely to compound
7 the problems since clock period P is very long. Long clock
8 periods may cause propagation delay D to vary over a wider
9 time interval. Thus, there is a need for a delay lock loop
10 which can maintain synchronization over a wide range of clock
11 frequencies and environmental extremes.

12 In addition, conventional delay lock loop circuits
13 provide for precise synchronization of the reference clock
14 signal REF_CLK and the skew clock signal S_CLK. It would be
15 desirable to have a delay lock loop circuit which is capable
16 of providing a skew clock signal S_CLK which is precisely
17 shifted by a relatively small amount with respect to the
18 reference clock signal REF_CLK. It would further be
19 desirable if such delay lock loop circuit were capable of
20 providing both a leading and lagging relationship. Such a
21 delay lock loop circuit would enable the precise control of
22 clock phase in logic circuits. Such control allows, for
23 example, more accurate timing budget allocation, which in
24 turn, allows synchronous digital systems to run at faster
25 speeds.

26 Delay lock loop circuit 100 provides an S_CLK signal
27 having a single frequency in response to the REF_CLK signal.
28 For example, the S_CLK signal may have a frequency of 100
29 MHz. The Federal Communications Commission (FCC) has
30 provided limits on the electromagnetic energy that a chip may
31 emit within a specified frequency bandwidth, which depends on
32 the characteristics of the system being tested. One such
33 measurement method employs a 1 MHz bandwidth window. Because
34 all of the energy emitted by the S_CLK signal exists at a
35 single frequency, all of the energy will also exist within
36 such a window. Therefore, for systems that violate FCC

limits, special techniques must be employed to reach compliance. Conventional compliance techniques include the use of stand-alone (i.e., off-chip) spread spectrum clock oscillators and metal shielding around the radiating components.

It would therefore be desirable to have a clock system that overcomes the electromagnetic emission limitations of delay lock loop 100.

SUMMARY OF THE INVENTION

The present invention provides a delay lock loop that synchronizes the reference clock signal with the skewed clock signal using a delay line having an initial propagation delay within a lock window. The lock window is a period of time between the minimum delay of the propagation delay and the maximum propagation delay. The extent of the lock window is chosen to ensure that changes in environmental conditions or clock frequencies, when compensated for by changing the propagation delay of the delay line, do not cause a loss of synchronization. A delay lock loop in accordance with one embodiment of the present invention incorporates a clock phase shifter in addition to the delay line to synchronize the reference clock. The increased flexibility provided by the clock phase shifter increases the range of frequencies at which the delay lock loop will operate.

The delay line receives the reference clock signal from a reference input terminal of the delay lock loop. The output of the delay line (i.e., the delayed clock signal) is provided to the clock phase shifter, which can generate one or more phase-shifted clock signals. An output generator receives the delayed clock signal and the one or more phase-shifted clock signals. The output generator provides one of the clock signals as the output clock signal on an output terminal. A phase detector compares the reference clock signal with the skewed clock signal, which is received on a feedback input terminal of the delay lock loop, to determine

1 whether to increase or decrease the propagation delay of the
2 delay line to synchronize the reference clock signal and the
3 skewed clock signal.

4 One embodiment of the clock phase shifter generates N-1
5 phase-shifted clock signals. Each of the phase-shifted clock
6 signals is phase-shifted from the other N-2 clock signals and
7 the delayed clock signal by $360/N$ degrees. For example, if
8 the clock phase shifter generated 3 phase-shifted clock
9 signals (i.e., N is equal to four), the phase-shifted clock
10 signals would be phase-shifted from the delayed clock signal
11 by 90 degrees, 180 degrees, and 270 degrees. The clock phase
12 shifter can be implemented using N delay lines and a phase
13 detector.

14 The delay lock loop can include a controller to control
15 the delay line and the output generator. In one embodiment
16 of the invention, the controller causes the output generator
17 to drive the delayed clock signal as the output clock. The
18 controller synchronizes the reference clock signal with the
19 skewed clock signal by adjusting the propagation delay of the
20 delay line to an initial delay. If the initial delay is not
21 within the lock window, the controller causes the output
22 generator to drive a first phase-shifted clock signal as the
23 output signal. The controller and phase detector then
24 synchronize the reference clock signal with the skewed clock
25 signal by adjusting the propagation delay of the delay line
26 to a second initial delay. If the second initial delay is
27 not within the lock window, the controller causes the output
28 generator to use a second phase-shifted clock signal as the
29 output clock. The controller continues in this manner until
30 an initial delay within the lock window is found.

31 In another embodiment of the invention, the clock phase
32 shifter is coupled to receive the reference clock signal.
33 The clock phase shifter generates phase-shifted clock signals
34 that are phase-shifted from the reference clock signals. The
35 reference clock signal or one of the phase-shifted clock
36 signals from the clock shifter is selected to be the input

1 signal of the delay line. The delay line is controlled by
2 the controller and the phase detector to delay the input
3 clock signal and synchronize the skewed clock signal with the
4 reference clock signal.

5 After the delay lock loop synchronizes the reference
6 clock signal with the skewed clock signal, a digital phase
7 shifter can be used to shift the skewed clock signal by a
8 small amount with respect to the reference clock signal. In
9 accordance with one embodiment, the tap settings and the
10 finer trim settings of a delay line in the clock phase
11 shifter are transmitted to the digital phase shifter, thereby
12 informing the digital phase shifter of the period of the
13 reference clock signal. In response, the digital phase
14 shifter provides a phase control signal that introduces a
15 delay, which is referenced to the period of the reference
16 clock signal, to either the reference clock signal or the
17 skew clock signal. The phase control signal is proportional
18 to a fraction of the period of the reference clock signal.
19 In one embodiment, the period of the reference clock signal
20 is determined from the tap/trim settings of a delay line in
21 the clock phase shifter. The delay line can have, for
22 example, 512 tap/trim units. The phase control signal is
23 determined by multiplying the equivalent tap/trim units used
24 by a delay line in the clock phase shifter by a fraction.
25 The fraction can be determined by the contents of
26 configuration memory bits stored in an FPGA, or by a user-
27 defined signal.

28 The digital phase shifter can be controlled to operate
29 in one of two fixed modes or in one of two variable modes.
30 In the first fixed mode, the digital phase shifter introduces
31 delay to the skew clock signal. For example, the digital
32 phase shifter can introduce a delay in the range of 0 to 511
33 tap/trim units to the skew clock signal in the first fixed
34 mode. In the second fixed mode, the digital phase shifter
35 introduces delay to the reference clock signal. For example,
36 the digital phase shifter can introduce a delay in the range

1 of 0 to 511 tap/trim units to the reference clock signal in
2 the second fixed mode. In the first variable mode, the
3 digital phase shifter can introduce a delay equal to 255 to -
4 255 tap/trim units to the reference clock signal. In the
5 second variable mode, the digital phase shifter can introduce
6 a delay equal to 255 to -255 tap/trim units to the skew clock
7 signal.

8 In accordance with another embodiment, the digital phase
9 shifter is capable of operating in a low frequency mode or a
10 high frequency mode. The digital phase shifter is controlled
11 to adjust the tap/trim setting provided by the delay line of
12 the clock phase shifter to compensate for different overhead
13 delays experienced by the clock phase shifter in the low
14 frequency mode and the high frequency mode.

15 In yet another embodiment of the present invention, the
16 frequency of the skew clock signal can be dithered around a
17 base frequency, thereby enabling this clock signal to comply
18 with FCC requirements for electromagnetic emissions in many
19 cases. That is, delay can be introduced such that the skew
20 clock signal exhibits slightly different frequencies in
21 successive periods. For example, the frequency of a 100 MHz
22 clock signal can be adjusted to have frequencies of
23 approximately 98, 98.5, 99, 99.5, 100, 100.5, 101, 101.5, and
24 102 MHz during different periods. This configuration is
25 referred to as a "spread-8" configuration, because eight
26 frequencies are generated in addition to the base frequency
27 of 100 MHz. For a 1 MHz window measurement method, because
28 the frequencies are spread in 0.5 MHz increments, only three
29 of the nine frequencies are included in the window. As a
30 result, 2/3 of the energy of the clock signal is not included
31 when determining whether the clock signal meets the FCC
32 electromagnetic emission requirements. By spreading the
33 frequencies above and below the base frequency in a regular
34 manner, the average frequency of the clock signal becomes
35 equal to the base frequency. Other configurations,
36 including, but not limited to, spread-2, spread-4 and spread-

6 configurations, can be implemented in accordance with the present invention.

In a preferred embodiment, the clock frequencies are generated by a digital spread spectrum (DSS) circuit, which operates with the digital phase shifter to insert small delays in the skew clock signal. Because the digital phase shifter delay must be able to adjust both up and down relative to its starting point, the variable mode of the digital phase shifter is typically used in conjunction with the DSS circuit. In accordance with one embodiment, the DSS circuit provides particular patterns of digital tap/trim adjustments to optimize the operation of the digital phase shifter.

In another embodiment, the DSS circuit and/or pattern of digital tap/trim adjustments necessary to successfully implement spread spectrum generation can be used with a conventional delay line, independent of the digital phase shifter.

The present invention will be more fully understood in view of the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a system using a conventional delay lock loop.

Figures 2A, 2B and 2C are timing diagrams for the system of Figure 1.

Figure 3 is a block diagram of a system using an embodiment of a delay lock loop in accordance with the present invention.

Figure 4 is a timing diagram for the delay lock loop of Figure 3.

Figure 5 illustrates a lock window as used in accordance with one embodiment of the present invention.

Figure 6 is a block diagram of an embodiment of a clock phase shifter in accordance with the present invention.

1 Figure 7 is a block diagram of another embodiment of a
2 clock phase shifter in accordance with the present invention.

3 Figure 8 is a block diagram of an output generator in
4 accordance with the present invention.

5 Figure 9 is a state diagram for an embodiment of a
6 controller in accordance with the present invention.

7 Figure 10 is a block diagram of a system using another
8 embodiment of a delay lock loop in accordance with the
9 present invention.

10 Fig. 11 is a block diagram of a delay lock loop, which
11 can be used in place of the delay lock loop of Fig. 3, in
12 accordance with another embodiment of the present invention.

13 Fig. 12 is a schematic diagram illustrating the tap/trim
14 delays for selected sections of a delay line in the clock
15 phase shifter of Fig. 7.

16 Fig. 13 is a block diagram of a digital phase shifter in
17 accordance with one embodiment of the present invention.

18 Figs. 14A and 14B are waveform diagrams illustrating
19 reference clock and skew clock signals for a first fixed mode
20 and a second fixed mode, respectively, of the delay lock loop
21 of Fig. 11.

22 Fig. 14C is a waveform diagram illustrating reference
23 clock and skew clock signals for a first and second variable
24 mode of the delay lock loop of Fig. 11.

25 Fig. 15 is a block diagram illustrating phase shift
26 control logic of Fig. 13 in more detail.

27 Fig. 16 is a block diagram of a digital spread spectrum
28 (DSS) circuit in accordance with another embodiment of the
29 present invention.

30 Fig. 17A is a graph illustrating a DSS bypass mode of
31 the DSS circuit of Fig. 16.

32 Fig. 17B is a graph illustrating a spread spectrum mode
33 of the DSS circuit of Fig. 16.

34 Fig. 18 is a circuit diagram of the DSS circuit of Fig.
35 16 in accordance with one embodiment of the present
36 invention.

Figs. 19A-19B are waveform diagrams illustrating reference clock and skew clock signal that result when the DSS circuit of Fig. 16 is controlled to implement a spread-8 configuration.

DETAILED DESCRIPTION OF THE DRAWINGS

Figure 3 is a block diagram of a system using a delay lock loop 300 in accordance with one embodiment of the present invention. Delay lock loop 300 comprises a delay line 310, a clock phase shifter 350, a controller 330, an output generator 340, and a phase detector 320. Delay lock loop 300 receives reference clock signal REF_CLK on a reference input terminal 302 and generates output clock signal O_CLK on output terminal 304. As explained above with respect to Figure 1, output clock signal O_CLK is skewed by clock skew 180 into skewed clock signal S_CLK, which clocks logic circuits 190. Skewed clock signal S_CLK is also fed back to a feedback terminal 306 of delay lock loop 300 on feedback path 170.

Within delay lock loop 300, reference clock signal REF_CLK is delayed by delay line 310 to generate delayed clock signal D_CLK. Delayed clock signal D_CLK is delayed from clock signal REF_CLK by a propagation delay D in delay line 310. One embodiment of delay lock loop 300 uses an adjustable delay line described in U.S. Patent Application Serial No. 09/102,704 [docket X-440 US], entitled "Glitchless Delay Line Using Gray Code Multiplexer", which is referenced above. However, other adjustable delay lines can also be used with delay lock loop 300. Delayed clock signal D_CLK is provided to an input terminal of a clock phase shifter 350 and to an input terminal of an output generator 340.

Clock phase shifter 350 generates one or more phase-shifted clock signals P_CLK_1 to P_CLK_N-1, where N is a positive integer. In one embodiment, phase-shifted clock signal P_CLK_1 is phase-shifted by $360/N$ degrees from delayed

1 clock signal D_CLK. Phase-shifted clock signal P_CLK_2 is
2 phase-shifted by $2 \cdot (360/N)$ degrees. Phase-shifted clock
3 signal P_CLK_N-1 is phase-shifted by $(N-1) \cdot (360/N)$ degrees.
4 Thus, in general a phase-shifted clock signal P_CLK_Z is
5 phase-shifted by $Z \cdot (360/N)$, where Z is an integer between 1
6 and (N-1), inclusive. Delayed clock signal D_CLK can be
7 considered a phase-shifted clock signal P_CLK_0 since delayed
8 clock signal D_CLK has a 0 degree phase shift from itself.
9 Further, in some embodiments of delay lock loop 300, clock
10 phase shifter 350 generates a phase-shifted signal P_CLK_N
11 that has the same phase and frequency as delayed clock signal
12 D_CLK.

13 Thus, in an embodiment of clock phase shifter 350 where
14 N is equal to four, phase-shifted clock signal P_CLK_1 is
15 phase-shifted 90 degrees from delayed clock signal D_CLK. It
16 logically follows that phase-shifted clock signal P_CLK_2 is
17 phase-shifted by 180 degrees from delayed clock signal D_CLK
18 and phase-shifted clock signal P_CLK_3 is phase-shifted by
19 270 degrees from delayed clock signal D_CLK. However, the
20 principles of the present invention are also suitable for
21 other embodiments of clock phase shifter 350 using other
22 patterns of phase shifting between the phase-shifted clock
23 signals.

24 Phase shifting is a concept in the frequency domain of a
25 clock signal. The equivalent of phase shifting in the time
26 domain is delaying the clock signal. Specifically, if a
27 first clock signal is phase-shifted from a second clock
28 signal by X degrees, the first clock signal is delayed by
29 $X \cdot (P/360)$, where P is the period of the first and second
30 clock signals. Thus, if phase-shifted clock signal P_CLK_1
31 is phase-shifted 90 degrees from delayed clock signal D_CLK,
32 phase-shifted clock signal P_CLK_1 is delayed by one-fourth
33 of the period of delayed clock signal D_CLK. To distinguish
34 delays caused by phase shifting from other propagation
35 delays, delays caused by phase shifting are referred to as
36 phase-shifted delays P_D_Z. Since a phase-shifted clock

1 signal P_CLK_Z is phase-shifted by $Z \cdot (360/N)$ degrees, phase-
2 shifted clock signal P_CLK_Z has a phase-shifted delay P_D_Z
3 equal to $Z \cdot (P/N)$, where Z is an integer between 1 and (N-1),
4 inclusive.

5 Figure 4 illustrates a timing diagram for delay lock
6 loop 300 (Figure 3) wherein N equals 4. Specifically, clock
7 phase shifter 350 generates phase-shifted clock signal
8 P_CLK_1 90 degrees out of phase with delayed clock signal
9 D_CLK. Thus, phase-shifted clock signal P_CLK_1 is delayed
10 by one-fourth of clock period P. Clock phase shifter 350
11 generates phase-shifted clock signal P_CLK_2 180 degrees out
12 of phase with delayed clock signal D_CLK. Thus, phase-
13 shifted clock signal P_CLK_2 is delayed by half of clock
14 period P. Finally, clock phase shifter 350 generates phase-
15 shifted clock signal P_CLK_3 270 degrees out of phase with
16 delayed clock signal D_CLK. Thus, phase-shifted clock signal
17 P_CLK_3 is delayed by three-fourths of clock period P.

18 Returning to Figure 3, clock phase shifter 350 provides
19 the phase-shifted clock signals to various input terminals of
20 output generator 340. In some embodiments of delay lock loop
21 300, clock phase shifter 350 can be configured using one or
22 more configuration signals CFG on an optional configuration
23 bus 360. An embodiment of clock phase shifter 350 that is
24 configured by configuration signals CFG is described below
25 with respect to Figure 7. Configuration signals CFG are
26 received on configuration terminals 308 and are routed to
27 clock phase shifter 350 and controller 330 by configuration
28 bus 360. Output generator 340 selects either delayed clock
29 signal D_CLK or one of the phase-shifted clock signals to
30 provide as output clock signal O_CLK. For embodiments of
31 delay lock loop 300 in which clock phase shifter 350 provides
32 phase-shifted clock signal P_CLK_N, output generator 340 can
33 use phase-shifted clock signal P_CLK_N in place of delayed
34 clock signal D_CLK. Controller 330 controls output generator
35 340.

1 Controller 330 receives phase information regarding
2 reference clock signal REF_CLK and skewed clock signal S_CLK
3 from phase detector 320. Specifically, phase detector 320
4 informs controller 330 whether propagation delay D from delay
5 line 310 should be increased or decreased to achieve
6 synchronization of skewed clock signal S_CLK with reference
7 clock signal REF_CLK. For embodiments of phase detector 320
8 that only determine whether to increase or decrease
9 propagation delay D, a jitter filter (not shown) can be used
10 to reduce clock jitter. In one embodiment, the jitter filter
11 is an up/down counter (not shown) that decrements by one if
12 propagation delay D should be decreased and increments by one
13 if propagation delay D should be increased. However,
14 propagation delay D is not adjusted until the up/down counter
15 reaches 0 or some other predetermined number. When
16 propagation delay D is adjusted, the up/down counter is reset
17 to one-half the maximum value. In other embodiments, phase
18 detector 320 calculates the amount propagation delay D should
19 be increased or decreased. During lock acquisition,
20 controller 330 attempts to synchronize skewed clock signal
21 S_CLK with reference clock signal REF_CLK so that initial
22 propagation delay ID of propagation delay D is within a lock
23 window W.

24 Figure 5 illustrates the concepts of lock window W. As
25 explained above, propagation delay D must be between minimum
26 propagation delay D_MIN and maximum propagation delay D_MAX.
27 Typical values for D_MIN and D_MAX are 3.2 nanoseconds and
28 46.8 nanoseconds, respectively. During lock acquisition,
29 controller 330 ensures that initial propagation delay ID of
30 propagation delay D is within lock window W. Specifically,
31 when synchronization is first established initial propagation
32 delay ID must be between lock window minimum W_MIN and lock
33 window maximum W_MAX. The limits on lock window W are set to
34 guarantee that once delay lock loop 300 completes locks
35 acquisition, delay lock loop 300 can maintain synchronization

as long as the system containing delay lock loop 300 operates within the design guidelines of the system.

For example, the system containing delay lock loop 300 generally can operate in a range of operating conditions. The range of operating conditions includes a maximum extreme condition in which propagation delay SKEW is maximized at a propagation delay value SKEW_MAX. Similarly, the range of operating conditions also includes a minimum extreme condition in which propagation delay SKEW is minimized at a propagation delay value SKEW_MIN. Thus, the maximum change (DELTA_SKEW) in propagation delay SKEW during operation of the system is equal to propagation delay value SKEW_MAX minus propagation delay value SKEW_MIN (i.e., $\text{DELTA_SKEW} = \text{SKEW_MAX} - \text{SKEW_MIN}$). For maximum protection during lock maintenance, lock window minimum W_MIN can be equal to minimum propagation delay D_MIN plus DELTA_SKEW. Similarly, lock window maximum W_MAX can be equal to maximum propagation delay D_MAX minus DELTA_SKEW. In one embodiment of the present invention, lock window minimum W_MIN is equal to approximately 16.5% of maximum propagation delay D_MAX and lock window maximum W_MAX is equal to approximately 67.8% of maximum propagation delay D_MAX.

As explained above with respect to Figure 1, for a conventional delay lock loop synchronization of skewed clock signal S_CLK with reference clock signal REF_CLK is achieved when propagation delay D plus propagation delay SKEW is equal to a multiple of period P. In equation form:

$$D + \text{SKEW} = \text{MULT}(P) \quad (1)$$

where MULT(P) refers to a multiple of P. Usually, the smallest multiple of P greater than SKEW is used.

With delay lock loop 300, controller 330 can also use the delays from the phase-shifted clock signals. Thus delay lock loop 300 can achieve synchronization if propagation delay D plus a phase-shifted delay P_D from a phase-shifted

clock signal plus propagation delay SKEW is a multiple of period P. In equation form:

$$D + P_D_Z + SKEW = MULT(P) \quad (2)$$

where P_D_Z refers to a phase-shifted delay from phase-shifted clock signal P_CLK_Z. Usually, the smallest multiple of P greater than propagation delay SKEW plus phase-shifted delay P_D_Z is used. As explained above with respect to Figure 3, in one embodiment of clock phase shifter 350 phase-shifted delay P_D_Z of a phase-shifted clock signal P_CLK_Z is equal to $Z*(P/N)$, where Z is an integer between 0 and (N-1), inclusive. If Z is equal to 0, controller 330 causes output generator 340 to use delayed clock signal D_CLK as output clock signal O_CLK. Thus, phase-shifted delay P_D_0 is equal to 0.

For clarity, initial delay ID can be referred to initial delay ID_0 if output generator 340 uses delayed clock signal D_CLK for output clock signal O_CLK. Similarly, initial delay ID can be referred to as initial delay ID_Z, if output generator 340 uses phase-shifted clock signal P_CLK_Z for output clock signal O_CLK, where Z is a positive integer between 1 and (N-1), inclusive. Thus, at the end of lock acquisition, equation (2) can be rewritten as:

$$ID_Z + P_D_Z + SKEW = MULT(P) \quad (3)$$

Re-arranging equation (3) provides:

$$ID_Z = MULT(P) - SKEW - P_D_Z \quad (4)$$

and substituting $Z*(P/N)$ for P_D_Z provides:

$$ID_Z = MULT(P) - SKEW - Z*(P/N) \quad (5)$$

1 Usually, the smallest multiple of P that results in a
2 positive initial delay ID_Z is used. In situations where
3 initial delay ID_Z is less than minimum propagation delay
4 D_MIN or greater than maximum propagation delay D_MAX, delay
5 lock loop 300 cannot synchronize skewed clock signal S_CLK
6 with reference clock signal REF_CLK using phase-shifted clock
7 signal P_CLK_Z.

8 Because controller 330 can select any one of phase-
9 shifted clock signals P_CLK_Z to drive output clock signal
10 O_CLK, controller 330 can select from N initial delay values.
11 The possible initial delay values range from a minimum offset
12 value ($MULT(P) - SKEW$) to a maximum value ($MULT(P) - SKEW$
13 $+ (N-1)/(N * \text{period } P)$). The difference between each
14 initial delay value is period P divided by N. For example,
15 if N equals four, period P equals 40 nanoseconds, and
16 propagation delay SKEW equals 25 nanoseconds; then initial
17 delays ID_0, ID_1, ID_2, and ID_3 equal 15 nanoseconds, 5
18 nanoseconds, 35 nanoseconds, and 25 nanoseconds, respectively
19 (as calculated using equation (5)). If N equals four, period
20 P equals 40 nanoseconds, and propagation delay SKEW equals 55
21 nanoseconds; then initial delays ID_0, ID_1, ID_2, and ID_3
22 equal 25 nanoseconds, 15 nanoseconds, 5 nanoseconds, and 35
23 nanoseconds, respectively. Thus, controller 330 is likely to
24 find one or more initial delay values within lock window W.
25 If more than one initial delay value is within lock window W,
26 controller 330 can select any one of the initial delay values
27 within lock window W.

28 Some embodiments of controller 330 can perform the
29 calculations described above to determine which phase-shifted
30 clock signal P_CLK_Z to use. However, other embodiments use
31 trial and error to determine which phase-shifted clock signal
32 P_CLK_Z to use. An embodiment of controller 330 that uses
33 trial and error is described below with respect to Figure 9.

34 Figure 6 illustrates one embodiment of clock phase
35 shifter 350 of Figure 3. The embodiment of clock phase
36 shifter 350 in Figure 6 comprises a phase detector 620 and a

1 plurality of delay lines 610_1 to 610_N. Delay lines 610_1
2 to 610_N are coupled in series. The input terminal of delay
3 line 610_1 receives an input clock signal such as delayed
4 clock signal D_CLK (Figure 3). The output terminal of delay
5 line 610_N is coupled to an input terminal of phase detector
6 620. Phase detector 620 also receives input clock signal
7 D_CLK on another input terminal. Phase detector 620 controls
8 all the delay lines in parallel via control line 625, and
9 each delay line provides the same amount of propagation
10 delay. Consequently, input clock signal D_CLK and the clock
11 signal P_CLK-N on the output terminal of delay line 610_N are
12 synchronized, i.e., in phase. Further, phase detector 620
13 causes the total propagation delay generated by delay lines
14 610_1 to 610_N to be equal to one period P of the input
15 clock. Thus, each delay line provides a propagation delay of
16 P/N . Thus, the output terminal of delay line 610_1 provides
17 a clock signal that is delayed from the input clock signal by
18 P/N whereas the output terminal of delay line 610_2 provides
19 a clock signal that is delayed from the input clock signal by
20 $2*P/N$. In general, the output terminal of delay line 610_Z
21 provides a clock signal that is delayed from the input clock
22 signal by $Z*P/N$, where Z is an integer between 1 and N-1,
23 inclusive. Accordingly, if the input clock signal is delayed
24 clock signal D_CLK, the output terminals of delay lines 610_1
25 to 610_N-1 provide phase-shifted clock signals P_CLK_1 to
26 P_CLK_N-1, respectively. Some embodiments of clock phase
27 shifter 350 also generate a clock signal P_CLK_N on the
28 output terminal of delay line 610_N that has the same phase
29 as delayed clock signal D_CLK.

30 Figure 7 shows a configurable embodiment of clock phase
31 shifter 350 of Figure 3. Specifically, the clock phase
32 shifter of Figure 7 can be configured in a first mode to
33 produce three phase-shifted clock signals that are 90
34 degrees, 180 degrees, and 270 degrees out of phase with an
35 input clock signal. In a second mode, the clock phase
36 shifter of Figure 7 produces a single phase-shifted clock

1 signal that is 180 degrees out of phase with the input clock
2 signal. The clock phase shifter of Figure 7 comprises a
3 phase detector 720, delay lines 710_1, 710_2, 710_3, and
4 710_4, and multiplexers 730_1, 730_2, 730_3, and 730_4. A
5 configuration line 740 is coupled to the select terminal of
6 multiplexers 730_1 to 730_4.

7 The input terminal of delay line 710_1 is coupled to
8 receive an input clock signal such as delayed clock signal
9 D_CLK (Figure 3). The output terminal of each delay line
10 710_Z is coupled to the logic one input terminal of
11 multiplexer 730_Z, where Z is an integer between 1 and 3,
12 inclusive. The output terminal of each multiplexer 730_Z is
13 coupled to the input terminal of delay line 710_Z+1, where Z
14 is an integer between 1 and 3, inclusive. The output
15 terminal of multiplexer 730_4 is coupled to an input terminal
16 of phase detector 720. The logic zero input terminals of
17 multiplexer 730_1 and multiplexer 730_3 are coupled to
18 ground. However, the logic zero input terminal of
19 multiplexer 730_2 is coupled to the output terminal of delay
20 line 710_1. Similarly, the logic zero input terminal of
21 multiplexer 730_4 is coupled to the output terminal of delay
22 line 710_3. Phase detector 720 also receives input clock
23 signal D_CLK on another input terminal. Phase detector 720
24 controls delay lines 710_1 to 710_4 in parallel as described
25 above with respect to phase detector 620.

26 If configuration line 740 is pulled to logic one, which
27 puts the embodiment of Figure 7 into the first mode, delay
28 lines 710_1 to 710_4 are coupled in series. In the first
29 mode, each delay line provides a delay of $P/4$. Thus, if the
30 input clock signal is delayed clock signal D_CLK, the output
31 terminal of each multiplexer 730_Z can provide phase-shifted
32 clock signals P_CLK_1, P_CLK_2, and P_CLK_3.

33 However, if configuration line 740 is pulled to logic
34 zero, which puts the embodiment of Figure 7 into the second
35 mode, only delay lines 710_1 and 710_3 are coupled in series.
36 Delay lines 710_2 and 710_4 have their input terminal coupled

1 to ground through multiplexers 730_1 and 730_3, respectively.
2 In the second mode delay lines 710_1 and 710_3 each provide a
3 delay of $P/2$. Coupling the input terminals of delay lines
4 710_2 and 710_4 to ground reduces power consumption and
5 switching noise. However, in the second mode the embodiment
6 of Figure 7 produces only one output clock signal, which is
7 180 degrees out of phase with the input clock signal and is
8 generated at the output terminal of multiplexer 730_2.

9 Figure 8 shows one embodiment of output generator 340 of
10 Figure 3. The output generator of Figure 8 comprises an N-
11 input multiplexer 810. N-input multiplexer 810 has N input
12 terminals, referenced as 810_0 to 810_N-1, select terminals
13 812, and an output terminal 814. When the embodiment of
14 output generator 340 of Figure 8 is used in delay lock loop
15 300 of Figure 3, select terminals 812 are coupled to
16 controller 330, input terminal 810_0 is coupled to receive
17 delayed clock signal D_CLK, output terminal 814 provides
18 output clock signal O_CLK, and input terminals 810_1 to
19 810_N-1 are coupled to receive phase-shifted clock signals
20 P_CLK_1 to P_CLK_N-1, respectively. Select signals on select
21 terminals 812 determine which input signal is provided on
22 output terminal 814. Other embodiments of output generator
23 340 may include additional circuitry, such as clock buffers
24 and clock dividers. In addition, some embodiments of output
25 generator 340 drive additional clock signals, such as various
26 versions of the phase-shifted clock signals.

27 Figure 9 shows a state diagram 900 for one embodiment of
28 controller 330 of Figure 3. On power-up or reset, controller
29 330 transitions to reset stage 910. In reset stage 910,
30 controller 330 sets a phase counter (not shown) to zero,
31 which causes output generator 340 to provide delayed clock
32 signal D_CLK as output clock signal O_CLK, and adjusts
33 propagation delay D of delay line 310 (Figure 3) to a
34 starting delay value. Starting delay values for propagation
35 delay D include, for example, minimum propagation delay
36 D_MIN, maximum propagation delay D_MAX, or the average of

1 minimum propagation delay D_MIN and maximum propagation delay
2 D_MAX. Controller 910 then transitions to lock acquisition
3 stage 920.

4 In lock acquisition stage 920, controller 330
5 synchronizes reference clock signal REF_CLK and skewed clock
6 signal S_CLK. Specifically, controller 330 adjusts
7 propagation delay D of delay line 310 based on signals from
8 phase detector 320. Phase detector 320 determines whether
9 propagation delay D must be increased or decreased to
10 synchronize skewed clock signal S_CLK with reference clock
11 signal REF_CLK. Lock acquisition is described above in
12 greater detail with respect to Figures 3-6; therefore, the
13 description is not repeated. In some embodiments, clock
14 phase shifter 350 is also reset by the power-on/reset signal.
15 For some of these embodiments, controller 330 does not adjust
16 propagation delay D until after clock phase shifter 350
17 produces phase-shifted clock signals P_CLK_1 to P_CLK_N-1.
18 If controller 330 cannot synchronize skewed clock signal
19 S_CLK with reference clock signal REF_CLK, controller 330
20 transitions to increment phase stage 950, described below.
21 Otherwise, controller 330 transitions to check lock window
22 stage 930 after controller 330 synchronizes skewed clock
23 signal S_CLK with reference clock signal REF_CLK (with an
24 initial propagation delay ID in delay line 310).

25 In check lock window stage 930, controller 330 must
26 determine whether initial propagation delay ID is within lock
27 window W. Specifically, propagation delay ID is within lock
28 window W if propagation delay ID is greater than lock window
29 minimum W_MIN and less than lock window maximum W_MAX. If
30 initial propagation delay ID is not within lock window W,
31 controller 330 transitions to increment phase stage 950.
32 Otherwise, controller 330 transitions to lock maintenance
33 stage 940.

34 In lock maintenance stage 940, controller 330 adjust
35 propagation delay D of delay line 310 to maintain
36 synchronization of skewed clock signal S_CLK with reference

1 clock signal REF_CLK. Lock maintenance is described above in
2 greater detail; therefore, the description is not repeated.
3 As described above, the present invention can maintain lock
4 throughout the systems environment conditions. Therefore,
5 controller 330 remains in lock maintenance stage 940 unless a
6 reset occurs that causes controller 330 to transition to
7 reset stage 910.

8 In increment phase stage 950, controller 330 increments
9 the phase counter, which causes output generator 340 to
10 select a different phase-shifted clock signal. Further,
11 controller 330 resets delay line 310 so that propagation
12 delay D returns to the starting delay value used in reset
13 stage 910. Controller 330 then transitions to lock
14 acquisition stage 920 and proceeds as described above.

15 Figure 10 is a block diagram of another embodiment of
16 delay lock loop 300. The embodiment of Figure 10 uses the
17 same principles as described above with respect to the
18 embodiment of Figure 3. However, in the embodiment of Figure
19 10, clock phase shifter 350 generates phase-shifted clock
20 signals P_CLK_1 to P_CLK_N-1 using reference clock signal
21 REF_CLK. Reference clock signal REF_CLK and phase-shifted
22 clock signals P_CLK_1 to P_CLK_N-1 are coupled to an input
23 selector 1040. Input selector 1040 selects either reference
24 clock signal REF_CLK or one of phase-shifted clock signals
25 P_CLK_1 to P_CLK_N-1 as a delay line input clock signal
26 DLI_CLK, which is provided to the input terminal of delay
27 line 310. Delay line 310 drives output clock signal O_CLK.
28 A controller 1030 controls input selector 1040 and delay line
29 310 based on the phase information provided by phase detector
30 320 so that delay line 310 provides a propagation delay D
31 that synchronizes skewed clock signal S_CLK with reference
32 clock signal REF_CLK. Input selector 1040 can be implemented
33 using the same circuit design as output generator 340.

34 In the various embodiments of the present invention,
35 novel structures have been described for delay lock loops.
36 By using a clock phase shifter to provide propagation delays

1 proportional to the period of a clock signal, the present
2 invention can provide clock signal control of the initial
3 propagation delay at lock acquisition. By accepting only
4 initial propagation delays within a lock window, the present
5 invention can maintain synchronization of the clock signals
6 over the entire range of environmental conditions of a system
7 using the present invention. Further, since the clock phase
8 shifter provides propagation delays proportional to the
9 period of the clock signal, the present invention is
10 applicable to systems using both high and low frequency clock
11 signals. In addition, the delay lock loop of the present
12 invention can be implemented with purely digital circuits
13 that can be completely incorporated on a single silicon chip
14 such as an FPGA, a DSP chip, or a microprocessor.

15 Fig. 11 is a block diagram of a delay lock loop 400,
16 which can be used in place of delay lock loop 300, in
17 accordance with another embodiment of the present invention.
18 Because delay lock loop 400 (Fig. 11) is similar to delay
19 lock loop 300 (Fig. 3), similar elements in Figs. 3 and 11
20 are labeled with similar reference numbers. Thus, delay lock
21 loop 400 includes delay line 310, phase detector 320,
22 controller 330, output generator 340, and clock phase shifter
23 350. In addition, delay lock loop 400 includes digital phase
24 shifter 1100, which enables the skew clock signal S_CLK to
25 have a leading or lagging relationship with respect to the
26 reference clock signal REF_CLK.

27 Within delay lock loop 400, both the reference clock
28 signal REF_CLK and the skew clock signal S_CLK are applied to
29 input terminals of digital phase shifter 1100. In response,
30 digital phase shifter 1100 provides phase shifted reference
31 clock signal PS_REF_CLK and phase shifted feedback clock
32 signal PS_S_CLK. The phase shifted reference clock signal
33 PS_REF_CLK is provided to input terminals of delay line 310
34 and phase detector 320. Thus, the PS_REF_CLK signal of delay
35 lock loop 400 is routed in the same manner as the reference
36 clock signal REF_CLK of delay lock loop 300. The phase

1 shifted feedback clock signal PS_S_CLK is provided to an
2 input terminal of phase detector 320. Thus, the PS_S_CLK
3 signal of delay lock loop 400 is routed in the same manner as
4 the skew clock signal S_CLK of delay lock loop 300.

5 As described in more detail below, digital phase shifter
6 1100 adjusts the phase relationship of the REF_CLK and S_CLK
7 signals to provide the PS_REF_CLK and PS_S_CLK signals,
8 respectively. As a result, the S_CLK signal can be
9 controlled to have a leading or lagging phase relationship
10 with respect to the REF_CLK signal.

11 In the described embodiment, clock phase shifter 350 is
12 configured in the manner illustrated in Fig. 7 (i.e., N=4).
13 Each of the delay lines 710_1, 710_2, 710_3 and 710_4
14 includes 128 tap delays and a trim delay circuit. The trim
15 delay circuit can be controlled to add up to 3 trim delays
16 between tap delays. Delay line 710_3 therefore has 512 (128
17 + 3*128) possible tap/trim delay settings. Fig. 12
18 illustrates the tap/trim delays for selected sections of
19 delay line 710_3. Circuitry for providing the tap/trim
20 delays is described in commonly owned, co-pending U.S. Patent
21 Application Serial No. 09/102,704, entitled "Glitchless Delay
22 Line Using Gray Code Multiplexer" by Andrew K. Percey, which
23 is incorporated herein by reference.

24 Phase detector 720 controls each of the delay lines
25 710_1, 710_2, 710_3 and 710_4 to have the same tap/trim
26 setting (+/- 1 trim delay). When the configuration signal
27 CFG has a logic "1" value (i.e., delay lock loop 400 is
28 configured in a low frequency mode), all four of the delay
29 lines 710_1, 710_2, 710_3 and 710_4 are coupled in series.
30 As a result, the delay selected by the tap/trim setting of
31 each of the delay lines corresponds with approximately one-
32 quarter cycle of the D_CLK signal.

33 Similarly, when the configuration signal CFG has a logic
34 "0" value (i.e., delay lock loop 400 is configured in a high
35 frequency mode), the two delay lines 710_1 and 710_3 are
36 coupled in series. As a result, the delay selected by the

1 tap/trim setting of each of the delay lines 710_1 and 710_3
2 corresponds with approximately one-half cycle of the D_CLK
3 signal.

4 Clock phase shifter 350 provides the tap/trim setting of
5 delay line 710_3 to digital phase shifter 1100, thereby
6 providing digital phase shifter 1100 with a signal that
7 corresponds with the period of the D_CLK signal. As
8 described in more detail below, this information is used to
9 select the phase shift introduced by digital phase shifter
10 1100.

11 Fig. 13 is a block diagram of digital phase shifter 1100
12 in accordance with one embodiment of the present invention.
13 Digital phase shifter 1100 includes multiplexers M0-M7,
14 overhead delay circuits 1301-1302, 64-tap delay circuit 1303,
15 adjustable 512-tap/trim delay line 1304, binary-to-gray
16 decoder 1305, phase shift control logic 1310 (which includes
17 up/down counter 1311) and DLL control circuitry 1312.

18 Digital phase shifter 1100 is controlled as follows.
19 First, digital phase shifter 1100 is selected to operate in
20 one of four modes. These four modes include a first fixed
21 mode, a second fixed mode, a first variable mode and a second
22 variable mode. In the first fixed mode, digital phase
23 shifter 1100 introduces delay to the skew clock signal. For
24 example, digital phase shifter 1100 can be controlled to
25 introduce a delay in the range of 0 to 511 tap/trim units to
26 the skew clock signal in the first fixed mode. In the second
27 fixed mode, digital phase shifter 1100 introduces delay to
28 the reference clock signal. For example, digital phase
29 shifter 1100 can be controlled to introduce a delay in the
30 range of 0 to 511 tap/trim units to the reference clock
31 signal in the second fixed mode. In the first variable mode,
32 digital phase shifter 1100 can be controlled to introduce a
33 delay equal to 255 to -255 tap/trim units to the reference
34 clock signal. In the second variable mode, digital phase
35 shifter 1100 can be controlled to introduce a delay equal to
36 255 to -255 tap/trim units to the skew clock signal.

1 The mode is selected in response to the S_LAGS_REF and
2 CENTERED control signals. The CENTERED control signal is de-
3 asserted low, and the S_LAGS_REF signal is de-asserted low to
4 indicate that the S_CLK signal will lead the REF_CLK signal
5 in the first fixed mode. Conversely, the CENTERED control
6 signal is de-asserted low, and the S_LAGS_REF signal is
7 asserted high to indicate that the S_CLK signal will lag the
8 REF_CLK signal in the second fixed mode. The CENTERED
9 control signal is asserted high and the S_LAGS_REF signal is
10 asserted high to enable the first variable mode. The
11 CENTERED control signal is asserted high and the S_LAGS_REF
12 signal is de-asserted low to enable the second variable mode.
13 In one embodiment, these control signals are provided by
14 configuration memory bits of a programmable logic device,
15 although this is not necessary.

16 Fig. 14A is a waveform diagram illustrating the REF_CLK
17 and S_CLK signals for the first fixed mode. To enter the
18 first fixed mode, the S_LAGS_REF control signal is de-
19 asserted to a logic "0" state, and the CENTERED control
20 signal is de-asserted to a logic "0" state. Under these
21 conditions, the REF_CLK signal is routed through multiplexers
22 M0, M2 and M6 and overhead delay circuit 1301 to provide the
23 PS_REF_CLK signal. The S_CLK signal is routed through
24 multiplexers M1, M4 and M7, overhead delay circuit 1302 and
25 512-tap/trim delay line 1304 to provide the PS_S_CLK signal.
26 Overhead delay circuits 1301 and 1302 introduce the same
27 delay to the applied signals. Thus, if the 512-tap/trim
28 delay line 1304 is set to have zero delay, then the REF_CLK
29 signal and the S_CLK signal will have identical delays
30 through digital phase shifter 1100.

31 Delay lock loop 400 will always cause the PS_REF_CLK and
32 the PS_S_CLK signals to be synchronized. As a result, any
33 phase shifting introduced by delay elements 1301-1304 is
34 realized by the REF_CLK and S_CLK signals. In the first
35 fixed mode, if the delay introduced by 512-tap/trim delay
36 line 1304 is increased, then the REF_CLK signal will lag the

1 S_CLK signal. The 512-tap/trim delay line 1304, which is
2 identical to delay line 710_3 (Fig. 7), can be configured to
3 provide a maximum tap/trim delay of 511 trim units (thereby
4 providing a maximum lag for the REF_CLK signal).

5 Fig. 14B is a waveform diagram illustrating the REF_CLK
6 and S_CLK signals for the second fixed mode. To enter the
7 second fixed mode, the S_LAGS_REF control signal is asserted
8 to a logic "1" state, and the CENTERED control signal is de-
9 asserted to a logic "0" state. Under these conditions, the
10 REF_CLK signal is routed through multiplexers M1, M2 and M6,
11 overhead delay circuit 1302 and 512-tap/trim delay line 1304
12 to provide the PS_REF_CLK signal. The S_CLK signal is routed
13 through multiplexers M0, M4 and M7 and overhead delay circuit
14 1301 to provide the PS_S_CLK signal. If the 512-tap/trim
15 delay line 1304 is set to have zero delay, then the REF_CLK
16 signal and the S_CLK signal will have identical delays
17 through digital phase shifter 1100.

18 In the second fixed mode, if the delay introduced by
19 512-tap/trim delay line 1304 is increased, then the REF_CLK
20 signal will begin to lead the S_CLK signal. When the 512-
21 tap/trim delay line 1304 is configured to provide a maximum
22 tap/trim delay of 511 trim units, a maximum phase lead will
23 be provided for the REF_CLK signal.

24 Fig. 14C is a waveform diagram illustrating the REF_CLK
25 and S_CLK signals for the first and second variable modes.
26 To enter the first variable mode, the CENTERED control signal
27 is asserted to a logic "1" state and the S_LAGS_REF control
28 signal is asserted to a logic "1" state. As a result, the
29 REF_CLK signal is routed through multiplexers M1, M3 and M6,
30 overhead delay circuit 1302 and 512-tap/trim delay line 1304
31 to provide the PS_REF_CLK signal. The S_CLK signal is routed
32 through multiplexers M0, M5 and M7, overhead delay circuit
33 1302 and 64-tap delay line 1303. The 64-tap delay circuit
34 1303 provides a fixed delay equal to half of the maximum
35 delay of 512-tap/trim delay line 1304 (or delay line 710_3).
36 The 512-tap/trim delay line 1304 is initially set to a delay

1 equal to zero trim units, and is incremented to a delay equal
2 to 64-taps (256 trim units). At this time, the delays
3 through delay circuits 1303 and 1304 are initially matched
4 (i.e., there is a zero phase shift). The delay introduced by
5 the 512-tap/trim delay line 1304 can be increased greater
6 than the 64 tap delay, thereby causing the S_CLK signal to
7 lag the REF_CLK signal. Conversely, the delay introduced by
8 the 512-tap/trim delay line 1304 can be reduced to less than
9 the 64 tap delay, thereby causing the S_CLK signal to lead
10 the REF_CLK signal. Because zero phase shift is obtained at
11 the mid-point of delay line 1304 (i.e., at 256 trim units),
12 this delay line 1304 can only provide an additional 255 trim
13 units of delay in each direction in the first variable mode.

14 Fig. 14C also represents the REF_CLK and S_CLK signals
15 for the second variable mode. To enter the second variable
16 mode, the CENTERED control signal is asserted to a logic "1"
17 state and the S_LAGS_REF control signal is asserted to a
18 logic "0" state. As a result, the REF_CLK signal is routed
19 through multiplexers M0, M3 and M4, overhead delay circuit
20 1301 and 64-tap delay line 1303 to provide the PS_REF_CLK
21 signal. The S_CLK signal is routed through multiplexers M1,
22 M6 and M7, overhead delay circuit 1301 and 512-tap/trim delay
23 line 1304. The 512-tap/trim delay line 1304 is initially set
24 to a delay equal to zero trim units, and is incremented to a
25 delay equal to 64-taps (256 trim units). At this time, the
26 delays through delay circuits 1303 and 1304 are initially
27 matched (i.e., there is a zero phase shift). The delay
28 introduced by the 512-tap/trim delay line 1304 can be
29 increased greater than the 64 tap delay, thereby causing the
30 S_CLK signal to lead the REF_CLK signal. Conversely, the
31 delay introduced by the 512-tap/trim delay line 1304 can be
32 reduced to less than the 64 tap delay, thereby causing the
33 S_CLK signal to lag the REF_CLK signal. The second variable
34 mode is similar to the first variable mode. However, in the
35 first variable mode, 512-tap/trim delay line 1304 is in line
36 with the REF_CLK signal, and in the second variable mode, the

1 512-tap/trim delay line 1304 is in line with the S_CLK
2 signal. In the described embodiments, the first variable
3 mode is preferred for the following reason. If the 512-
4 tap/trim delay line 1304 is in line with the S_CLK signal,
5 then delay line 310 will subsequently need to compensate for
6 adjustments made by delay line 1304, thereby reducing the
7 number of available tap adjustments remaining in delay line
8 310.

9 Delay lock loop 400 operates as follows in accordance
10 with one embodiment of the present invention.

11 Initially, configuration memory bits are set to define
12 the states of the S_LAGS_REF and CENTERED control signals,
13 thereby defining whether digital phase shifter 1100 will
14 operate in the first fixed mode (REF_CLK lagging S_CLK), the
15 second fixed mode (REF_CLK leading S_CLK) or the first or
16 second variable mode.

17 Configuration memory bits are also set to define the
18 states of the PS_SIGN, PS_MAG[7:0], HF_MODE, LFC and HFC
19 control signals. The PS_MAG[7:0] control signal identifies
20 the magnitude of the phase shift to be introduced by digital
21 phase shifter 1100. The PS_SIGN control signal is used to
22 identify the polarity of the PS_MAG[7:0] signal when digital
23 phase shifter 1100 is configured in the variable mode (i.e.,
24 CENTERED = 1). When digital phase shifter 1100 is configured
25 in a fixed mode, the PS_SIGN control signal is not used. If
26 the PS_SIGN signal has a logic "1" state (indicating a
27 negative polarity), the PS_MAG[7:0] signal cannot have a
28 logic 0 value, because the PS_MAG[7:0] signal is represented
29 in 2's complement in the present embodiment.

30 The HF_MODE control signal is set to a logic "0" value
31 when digital phase shifter 100 is operating in response to
32 low frequency clock signals, where all four delay lines
33 710_1-710_4 are required to create one full period.
34 Conversely, the HF_MODE control signal is set to a logic "1"
35 value when digital phase shifter 1100 is operating in
36 response to high frequency clock signals, where only two

1 delay lines 710_1 and 710_3 are sufficient to create one full
2 period. The HF_MODE control signal is used to select a low
3 frequency mode constant LFC[7:0] or a high frequency mode
4 constant HFC[7:0].

5 The low frequency mode constant LFC[7:0] represents the
6 overhead of the signal path in trim units through the delay
7 chain located in clock phase shifter 350 (Fig. 7), when the
8 CFG signal has a logic "1" value and all of the tap/trim
9 settings in delay lines 710_1-710_4 are set to zero.

10 Similarly, the high frequency mode constant HFC[7:0]
11 represents the overhead of the signal path in trim units
12 through the delay chain located in clock phase shifter 350
13 (Fig. 7), when the CFG signal has a logic "0" value and all
14 of the tap/trim settings in delay lines 710_1 and 710_3 are
15 set to zero. The low frequency mode constant LFC[7:0] and
16 the high frequency mode constant HFC[7:0] are determined by
17 Spice simulation in the described embodiment.

18 After the above-described constants have been set, the
19 RESET signal is asserted, thereby resetting up/down counter
20 1311 to a value corresponding with zero tap/trim delay in
21 delay line 1304. Delay line 310 is also set to a value
22 corresponding with zero tap/trim delay. These settings are
23 maintained until after clock phase shifter 350 achieves a
24 locked condition. More specifically, the REF_CLK signal is
25 routed through digital phase shifter 1100 and delay line 310,
26 and is provided to clock phase shifter 350 (as the D_CLK
27 signal). In response, clock phase shifter 350 operates in
28 the manner described above in connection with Fig. 7 to
29 achieve a locked condition with respect to the REF_CLK
30 signal. Note that digital phase shifter 1100 and delay line
31 310 are prevented from adjusting their delay lines while
32 clock phase shifter 350 is locking using the REF_CLK signal.
33 After clock phase shifter 350 has achieved a locked
34 condition, the tap/trim setting of delay line 710_3 is
35 representative of either $\frac{1}{4}$ of the period (low frequency mode)
36 or $\frac{1}{2}$ of the period (high frequency mode) of the reference

1 clock signal REF_CLK. At the end of this state, the tap/trim
2 setting of delay line 710_3 is provided to phase shift
3 control logic 1310 as the TAP_TRIM[8:0] signal. The RESET
4 signal is de-asserted after the clock phase shifter 350 is
5 locked.

6 After the RESET signal is de-asserted, digital phase
7 shifter 1100 is allowed to adjust delay line 1304. However,
8 while digital phase shifter 1100 is adjusting delay line
9 1304, clock phase shifter 350 and delay line 310 are
10 prevented from adjusting their delay lines. Digital phase
11 shifter 1100 increments counter 1311 to provide the initial
12 setting of 512-tap/trim delay line 1304. The initial setting
13 of 512-tap/trim delay line 1304 is calculated as a function
14 of the TAP_TRIM[8:0] signal and the PS_SIGN and PS_MAG[6:0]
15 values. Up/down counter 1311 is incremented (or decremented)
16 until the count of this counter 1311 matches the calculated
17 initial setting. This count is transparently passed to 512-
18 tap/trim delay line 1304 through binary-to-gray code
19 converter 1305. Binary-to-gray code converter is described
20 in more detail in commonly owned, co-pending U.S. Patent
21 Application Serial No. 09/102,704.

22 More specifically, the initial setting of 512-tap/trim
23 delay line 1304 is determined by first determining an
24 equivalent tap/trim per period (ETT/P). For low frequency
25 mode, ETT/P is determined by the following equation.

26
27
$$\text{ETT/P} = (4 \times (\text{TAP_TRIM}[8:0])) + \text{LFC}[7:0] \quad (6)$$

28
29 For high frequency mode, ETT/P is determined by the
30 following equation.

31
32
$$\text{ETT/P} = (2 \times (\text{TAP_TRIM}[8:0])) + \text{HFC}[7:0] \quad (7)$$

33
34 The initial setting of 512-tap/trim delay line 1304 is
35 then determined from the ETT/P value in the following manner.
36 For the first and second fixed modes of operation, the

1 initial tap/trim setting of 512-tap/trim delay line 1304 is
2 equal to:

3

$$4 \quad (PS_MAG[7:0]/256) \times ETT/P \quad (8)$$

5

6 For the first and second variable modes of operation,
7 the initial tap/trim setting of 512-tap/trim delay line 1304
8 is equal to:

9

$$10 \quad 256 + ((PS_MAG[7:0]/256) \times ETT/P); \quad (9)$$

11 If PS_SIGN = 0

12

13 or

14

$$15 \quad 256 - ((PS_MAG[7:0]/256) \times ETT/P); \quad (10)$$

16 If PS_SIGN = 1.

17

18 Because there is only one delay line 1304 in digital
19 phase shifter 1100, the maximum value of PS_MAG[7:0]/256 is
20 less than approximately $\frac{1}{4}$ and $\frac{1}{2}$ of the longest period, for
21 the low and high frequency modes, respectively.

22 After the initial tap/trim setting of 512-tap/trim delay
23 line 1304 has been set, digital phase shifter 1100 and clock
24 phase shifter 350 are temporarily prevented from adjusting
25 their delay lines. At this time, delay line 310 is released,
26 thereby enabling delay line 310 to be adjusted, such that the
27 PS_REF_CLK and the PS_S_CLK signals are synchronized. That
28 is, delay line 310 is allowed to achieve a locked condition.
29 At this time, the S_CLK and REF_CLK signals exhibit a skew
30 corresponding with the delay introduced by 512-tap/trim delay
31 line 1304. In general processing continues in the above-
32 described manner, such that during the next state, clock
33 phase shifter 350 is allowed to lock, while delay line 1304
34 in digital phase shifter 1100 and delay line 310 are held at
35 their previously determined values. During the next state,
36 delay line 1304 of digital phase shifter 1100 is allowed to

1 lock (using the TAP_TRIM[8:0] signal determined by clock
2 phase shifter 350 during the previous state), while delay
3 line 310 and the delay line in clock phase shifter 350 are
4 held at their previously determined values. During the next
5 state, delay line 310 is allowed to lock, while delay line
6 1304 of digital phase shifter 1100 and the delay line in
7 clock phase shifter 350 are held at their previously
8 determined values. By allowing only one of delay line 310,
9 clock phase shifter 350 and digital phase shifter 1100 to
10 adjust their delay lines at any given time, contention is
11 prevented between delay line 310, clock phase shifter 350 and
12 digital phase shifter 1100.

13 A more detailed description of the state machine used to
14 control delay line 310, clock phase shifter 350 and digital
15 phase shifter 1100 is provided in Appendix A.

16 As described above, the tap/trim setting of 512-tap/trim
17 delay line 1304 is periodically recalculated, using the
18 current TAP_TRIM[8:0] value provided by delay line 710_3 of
19 clock phase shifter 350. Up/down counter 1311 is
20 incremented, unchanged, or decremented, depending on whether
21 the new TAP_TRIM[8:0] value is greater, the same or less than
22 the old TAP_TRIM[8:0] value, respectively. As described
23 above, a delay lock loop manager (not shown) ensures that
24 delay line 310 and clock phase shifter 350 never check phase
25 on a cycle that is temporarily extended or shortened by a
26 trim change implemented within 512-tap/trim delay line 1304.

27 The tap/trim setting of delay line 1304 can also be
28 modified by the user of delay lock loop 400 through a user
29 interface 1320. User interface 1320 includes the phase
30 increment/decrement signal PSINCDEC, the phase shift enable
31 signal PSEN, the phase shift clock signal PSCLK and the phase
32 shift done signal PSDONE, which are provided to phase shift
33 control logic 1310. The PSCLK signal is different than the
34 PS_DLY_OUT clock signal, thereby requiring the coordination
35 of these two clock domains within phase shift control logic
36 1310. The PSEN signal is asserted high for one cycle of the

1 PSCLK signal. At the same time, or prior to this cycle, the
2 PSINCDEC signal is asserted high or low, thereby causing the
3 numerator of the fraction in equations (8), (9) or (10) to be
4 incremented or decremented by one, respectively. If the
5 increment or decrement in the numerator is sufficient to
6 warrant a change in the count value in up/down counter 1311,
7 then this change is implemented. When digital phase shifter
8 1100 has completed the increment or decrement operation,
9 phase shift control logic 1310 asserts the PSDONE signal for
10 one cycle of the PSCLK signal, thereby indicating to the user
11 that the tap/trim setting of delay line 1304 can be modified
12 again.

13 Fig. 15 is a block diagram illustrating phase shift
14 control logic 1310 in more detail. In the described
15 embodiment, phase shift control logic 1310 includes
16 multiplexers 1501-1506, up/down signed counter 1511,
17 registers M0-M1, adder 1531, bias adder/subtractor 1532,
18 comparator block 1533, product register 1541, OR gate 1542,
19 AND gate 1543, control block 1550 and up/down counter 1311.

20 Phase shift control logic 1310 performs the mathematics
21 to convert the TAP_TRIM[8:0], LFC[7:0], HFC[7:0], PS_SIGN and
22 PS_MAG[7:0] signals to the PS_TT[8:0] value, such that the
23 phase shift delay introduced by delay line 1304 is the
24 desired fractional part of the clock period. Phase shift
25 control logic 1310 also includes a user interface 1320 that
26 allows dynamic phase adjustments, and an interface to DLL
27 control 1312.

28 DLL control 1312 specifies when phase shift control
29 logic 1310 may change the PS_TT[8:0] signal. DLL control
30 1312 does this with an asynchronous 4 wave front hand shake
31 cycle between the GO signal (a request from DLL control 1312)
32 and the DONE signal (a response from phase shift control
33 logic 1310).

34 The first GO signal asserted after the RESET signal
35 causes the PS_TT[8:0] signal to increment from zero to the
36 correct initial setting. On subsequent cycles, the

1 PS_TT[8:0] signal is unchanged, increased, or decreased to
2 maintain the correct delay (i.e., the currently specified
3 fractional portion of the REF_CLK period).

4 A primary state machine of phase shift control logic
5 1310 remains dormant until the GO signal is received from DLL
6 control 1312. After the GO signal is captured and
7 synchronized to the local clock signal, this primary state
8 machine is used to calculate the current PS_TT[8:0] per
9 equations (6)-(10) provided above. When the calculation and
10 PS_TT update is completed, the DONE signal is activated to
11 inform DLL control 1312 that the operation is complete.
12 After the primary state machine is started, control proceeds
13 to the next state after one clock cycle, unless otherwise
14 noted. The various states of the primary state machine will
15 now be described.

16 During an IDLE state, the PS_SIGN and PS_MAG[7:0]
17 signals are loaded into up/down signed counter 1511. Signed
18 counter 1511 provides the PS_SIGN signal as the SIGN signal,
19 and the PS_MAG[7:0] signal as the PS[7:0] signal. The
20 PS[7:0] signal is loaded into register M0.

21 In addition, the HF_MODE signal causes either the
22 HFC[7:0] value or the LFC[7:0] value to be routed through
23 multiplexer 1501. In the described example, the HF_MODE
24 signal has a logic "0" value (low frequency mode), thereby
25 causing the LFC[7:0] value to be passed. Multiplexers 1502,
26 1503 and 1504 are controlled to pass the LFC[7:0] value from
27 the output of multiplexer 1501 to register M1. The LFC[7:0]
28 value is loaded into register M1, thereby completing the IDLE
29 state.

30 The primary state machine then enters an M1_TO_PROD
31 state, in which the contents of register M1 are transferred
32 into product register 1541. Note the product register 1541
33 was initially reset to store a logic zero value. Adder 1531
34 initially adds this initial zero value (on the B input
35 terminal of adder 1531) to the contents of register M1 (on
36 the A input terminal of adder 1531). The result (i.e., the

1 LFC[7:0] constant) is loaded into product register 1541,
2 thereby completing the M1_TO_PROD state.

3 The primary state machine then enters a TAP_TRIM_TO_M1
4 state, where the TAP_TRIM[8:0] signal is loaded into register
5 M1. The primary state machine controls the multiplexers
6 1502-1504 to route the TAP_TRIM[8:0] signal to register M1.

7 The primary state machine then enters a SHIFT1 **state**, in
8 which the TAP_TRIM[8:0] signal is multiplied by 2. This is
9 accomplished by routing the TAP_TRIM[8:0] signal from the
10 output of register M1 to the "1" input terminal of
11 multiplexer 1506. This path shifts the TAP_TRIM[8:0] signal
12 left by one bit, thereby effectively multiplying the
13 TAP_TRIM[8:0] signal by 2. This corresponds with the
14 multiply by 2 function described above in equation (7). The
15 shifted TAP_TRIM[8:0] signal is routed through multiplexers
16 1506, 1503 and 1504 and is re-loaded into register M1.

17 If the HF_MODE signal has a logic "0" state (i.e., low
18 frequency mode), then the primary state machine enters a
19 SHIFT2 state, in which the TAP_TRIM[8:0] signal is again
20 multiplied by 2 (thereby providing the multiply by four
21 function required by equation (6)). The multiply by 2
22 operation of the SHIFT2 state is performed in the same manner
23 as the multiply by 2 operation of the SHIFT1 state. If the
24 HF_MODE signal has a logic "1" state (i.e., high frequency
25 mode), then the primary state machine skips the SHIFT2 state.

26 The primary state machine then enters a ETP_TO_M1
27 state, in which the shifted TAP_TRIM[8:0] signal stored in
28 register M1 is added to the LFC[7:0] constant stored in
29 product register 1541, thereby creating the ETT/P value. To
30 accomplish this, adder 1531 is controlled to add the contents
31 of register M1 (i.e., the shifted TAP_TRIM[8:0] value) and
32 the contents of product register 1541 (i.e., the LFC[7:0]
33 constant). The result (i.e., the ETT/P value) is routed
34 through multiplexer 1504 and loaded into register M1.

1 The primary state machine then enters a RST_PROD state,
2 in which the contents of product register 1541 are reset to a
3 zero value.

4 The primary state machine then enters a MULTIPLY state,
5 in which the ETT/P value stored in register M1 is multiplied
6 by the PS[7:0] value stored in register M0. The 19-bit adder
7 1531 is used to multiply these values, using an iterative add
8 and shift method. Thus, adder 1531 initially adds zero to
9 the ETT/P value, such that the ETT/P value is initially
10 provided to the input terminal of product register 1541. At
11 this time, the PS[0] bit is provided to the load terminal of
12 product register 1541. If the PS[0] bit has a logic "1"
13 value, then the ETT/P value is loaded into product register
14 1541. If the PS[0] bit has a logic "0" value, then the ETT/P
15 value is not loaded into product register 1541 (i.e., product
16 register 1541 continues to store a zero value). The contents
17 of product register 1541 are provided to the B input terminal
18 of adder 1531 as the P[18:0] signal.

19 After this first iteration, the PS[7:0] value is shifted
20 to the right by one bit, such that register M0 provides the
21 PS[1] bit to the load input terminal of product register
22 1541. Also after the first iteration, the ETT/P value stored
23 in register M1 is shifted to the left by one bit by routing
24 this value through the left-shifting input terminal of
25 multiplexer 1506 and multiplexers 1503-1504. This left-
26 shifted ETT/P value is loaded into register M1. Adder 1531
27 then provides an output equal to the sum of the left shifted
28 ETT/P value and the contents of product register 1541. If
29 the PS[1] bit has a logic "1" value, then the output of adder
30 1531 is loaded into product register 1541. If the PS[1] bit
31 has a logic "0" value, then the output of adder 1531 is not
32 loaded into product register 1541, and the contents of
33 product register 1541 remain unchanged.

34 This process is repeated, with the ETT/P value stored in
35 register M1 being shifted left and the PS[7:0] signal in
36 register M0 being shifted right on each iteration. The

1 process is completed when bits M0[7:1] all have logic "0"
2 values. At this time, product register 1541 holds a value
3 equal to $ETT/P \times PS_MAG$ (see equations (8), (9), (10)). If
4 either one of bits P[18:17] provided by product register 1541
5 has a logic "1" value, then an overflow condition exists.
6 Under these conditions, OR gate 1542 provides a logic high
7 OVERFLOW signal, and product register 1541 is prevented from
8 changing state until the MULTIPLY state is exited.

9 After the MULTIPLY state is complete, the primary state
10 machine enters a PASS state. During the PASS state, bias
11 adder/subtractor 1532 is allowed time to complete an add or
12 subtract operation. Bits P[16:8] of product register 1541
13 are provided to the "A" input terminal of bias
14 adder/subtractor 1532, thereby right shifting the contents of
15 product register 1541 by 8 bits. This effectively divides
16 the contents of product register by 256 (see equations
17 (8), (9), (10)). The "B" input terminal of bias
18 adder/subtractor 1532 is coupled to receive a value of either
19 "0" (if CENTERED = 0) or 256 (if CENTERED = 1). Bias
20 adder/subtractor 1532 will perform an addition (B+A) if AND
21 gate 1543 provides a logic "0" output signal. Conversely,
22 bias adder/subtractor 1532 will perform a subtraction (B-A)
23 if AND gate 1543 provides a logic "1" output signal. AND
24 gate 1543 only provides a logic "1" signal if delay lock loop
25 400 is configured in the variable mode (CENTERED = 1), and
26 up/down signed counter 1511 has a negative value (SIGN = 1).
27 If bit R[9] of bias adder/subtractor 1532 has a logic "1"
28 value, OR gate 1542 will assert the OVERFLOW signal, thereby
29 indicating that an overflow condition exists. As long as the
30 OVERFLOW signal is not asserted, the result R[8:0] provided
31 by bias adder/subtractor 1532 represents the desired
32 PS_TT[8:0] signal.

33 Note that the OVERFLOW signal can be set due to any of
34 the following: (a) the value provided by product register
35 1541 is not between 0 and 1FFFF, inclusive, (b) the R[8:0]
36 output of bias adder/subtractor 1532 is not between 0 and

1 1FF, inclusive (c) tap/trim counter 1311 would wrap if
2 changed in the selected direction, and (d) up/down counter
3 1511 would wrap if changed in the selected direction.

4 After the PASS state is complete, the primary state
5 machine enters an ADJUST_PSTT state. In this state, the
6 PS_TT[8:0] signal is set equal to the result R[8:0] provided
7 by bias adder/subtractor 1532. The "A" input terminal of
8 comparator 1533 is coupled to receive the result R[8:0] of
9 bias adder/subtractor 1532. The "B" input terminal of
10 comparator 1533 is coupled to receive the PS_TT[8:0] signal
11 from up/down counter 1311. Comparator 1533 provides logic
12 high signal to the clock enable input terminal (CE) of
13 up/down counter 1311 if the R[8:0] signal is not equal to the
14 PS_TT[8:0] signal, thereby enabling up/down counter 1311.
15 Comparator 1533 also provides a logic high signal to the UP
16 terminal of up/down counter 1311 if the PS_TT[8:0] signal is
17 less than the R[8:0] signal. Conversely, logic block 1533
18 provides a logic low signal to the UP terminal of up/down
19 counter 1311 if the PS_TT[8:0] signal is greater than or
20 equal to the R[8:0] signal. Up/down counter 1311 is
21 incremented by one if the UP terminal receives a logic "1"
22 signal, and is decremented by one if the UP terminal receives
23 a logic "0" signal. Upon RESET, up/down counter 1311 is
24 reset to a logic zero value. Consequently, up/down counter
25 1311 will adjust the PS_TT[8:0] value until this value is
26 equal to the R[8:0] value (or until overflow occurs). When
27 the PS_TT[8:0] signal is equal to the R[8:0] signal, or
28 OVERFLOW is true, control logic 1550 sets the DONE signal.
29 Control logic 1550 sets the PS_LOCKED signal the first time
30 the DONE signal is asserted after RESET. The PS_LOCKED
31 signal informs DLL control 1312 that the phase shift logic
32 1310 has been properly initialized. An exception is during
33 the locking process, where the DONE signal is not set if
34 OVERFLOW is true, so the PS_LOCKED signal will not set
35 either.

1 The primary state machine then enters the WT_GONOT
2 state, in which the state machine waits until the GO signal
3 is inactive, and then enters the IDLE state.

4 External user interface 1320 is provided to allow
5 dynamic changes to the phase shift (i.e., the fraction
6 numerator of equations (8),(9),(10)) during normal operation.
7 The user may increment or decrement the fraction numerator.
8 In the variable modes, the fraction numerator may cross from
9 positive through zero to negative, and vice-versa. External
10 user interface 1320 is synchronous with the external clock
11 signal PSCLK. Note that the rest of the clocked elements of
12 phase shift control circuit 1310 are clocked by the
13 PS_DLY_OUT clock signal. The module uses standard techniques
14 to cross from the PSCLK domain to the PS_DLY_OUT clock domain
15 and vice-versa.

16 A second state machine, namely, a dynamic phase change
17 (DPS) state machine, controls user interface 1320. Running
18 in the PS_DLY_OUT clock domain, the DPS state machine also
19 ensures that changes are made to the signed up/down counter
20 1511 only when this counter is not being used by the primary
21 state machine. After the DPS state machine is started,
22 control proceeds to the next state after one clock cycle,
23 unless otherwise noted in the description below.

24 The DPS state machine starts in a DPS_IDLE state,
25 wherein the state machine waits for the PSEN signal to be
26 asserted. Upon detecting the PSEN signal (as clocked in by
27 the PSCLK signal), the DPS state machine will proceed to the
28 next state. However, to avoid logical discontinuity, the
29 DPS_IDLE state cannot be exited unless the primary state
30 machine is in the IDLE state.

31 The DPS state machine then enters a DPS_CNTR state, in
32 which counter 1511 is incremented if the captured PSINCDEC
33 signal has a logic "1" value, and decremented if the captured
34 PSINCDEC signal has a logic "0" value.

35 The DPS state machine then enters a DPS_W_ADJUST_PSTT
36 state, in which the DPS state machine waits until the primary

1 state machine completes a corresponding adjustment cycle.
2 The DPS state machine remains in this state until the exit
3 conditions for the primary state ADJUST_PSTT are true.

4 The DPS state machine then enters a DPS_SETDONE state,
5 in which the PSDONE signal (which is coupled to the PSCLK
6 domain) is set. The asserted PSDONE signal informs the user
7 that the requested phase change has been completed.
8 Processing then returns to the DPS_IDLE state.

9 In the foregoing manner, digital phase shifter 1100 is
10 capable of precisely modifying the delay between the REF_CLK
11 and S_CLK signals. This operation is controlled to
12 compensate for low frequency and high frequency signals, as
13 well as for variations in temperature. Advantageously, the
14 phase can be modified both automatically and under user
15 control.

16 Fig. 16 is a block diagram of a digital spread spectrum
17 (DSS) circuit 1600 in accordance with another embodiment of
18 the present invention. DSS circuit 1600 is coupled between
19 up/down counter 1311 and binary-to-gray conversion circuit
20 1305 (See, Fig 13). Both up/down counter 1311 and DSS
21 circuit 1600 are clocked by the PS_DLY_OUT signal. In
22 general, DSS circuit 1600 can be configured to add or
23 subtract small predetermined values to the PS_TT[8:0] signal
24 to create the JOINT_TT[8:0] signal. In this case, DSS
25 circuit 1600 is in a spread spectrum mode. While in the
26 spread spectrum mode, the JOINT_TT[8:0] signal causes small
27 variations in the clock period of the PS_DLY_OUT signal.

28 DSS circuit 1600 can also be configured to disable the
29 spread spectrum mode, such that the PS_TT[8:0] signal is
30 transmitted through DSS circuit 1600 without change. This is
31 referred to as the DSS bypass mode.

32 Fig. 17A illustrates the DSS bypass mode, in which the
33 PS_DLY_OUT signal has a frequency of 100 MHz and an energy of
34 X. In determining the electromagnetic emission of the chip,
35 the FCC will use a window 1701 having a specified width
36 (e.g., 1 MHz). Because the PS_DLY_OUT signal has a single

1 frequency, the 1 MHz window 1701 will capture all of the
2 energy X of the PS_DLY_OUT signal.

3 Fig. 17B illustrates one of the spread spectrum modes of
4 DSS circuit 1600, in which the PS_DLY_OUT signal is
5 controlled to exhibit frequencies of approximately 98, 98.5,
6 99, 99.5, 100, 100.5, 101, 101.5 and 102 MHz. Because each
7 of these frequencies exists only 1/9 of the time, the
8 PS_DLY_OUT signal has an energy of 1/9 X at each of these
9 frequencies. As a result, the 1 MHz window 1701 will only
10 capture three of the nine frequencies at any given time. As
11 a result, the energy detected by the 1 MHz window has a
12 maximum value of 1/3 X. This represents a significant
13 reduction in EMI energy versus the bypass mode. As the base
14 frequency of the PS_DLY_OUT signal changes, the number of
15 frequencies existing within the 1 MHz window may change.

16 Fig. 18 is a circuit diagram of DSS circuit 1600 in
17 accordance with one embodiment of the present invention. DSS
18 circuit 1600 includes pattern generator 1801, signed adder
19 1802, pipeline register 1803, 5-bit up counter 1804, D flip-
20 flops 1805-1806, inverter 1807, OR gate 1808, and NAND gate
21 1809. The elements of DSS circuit 1600 are clocked by the
22 PS_DLY_OUT signal.

23 To enable DSS circuit 1600, a configuration memory bit
24 is programmed to store a logic low EN_DSS# signal, thereby
25 enabling the user to select whether or not the DSS circuit
26 1600 can be used during normal operation of delay lock loop
27 400. If the user wants to use DSS circuit 1600, the user
28 must also provide a logic high DSS_EN signal to NAND gate
29 1809. The RESET signal is then asserted high, which causes
30 OR gate 1808 to provide a logic high signal to clear pattern
31 generator 1801, clear flip-flop 1805, and asynchronously set
32 5-bit up counter 1804 to a value of "10000" (i.e., binary
33 16).

34 Initially, delay lock loop 400 is not locked (i.e.,
35 DLL_LOCKED is low). As a result, NAND gate provides a logic
36 "1" value, which is loaded into flip-flop 1805. This logic

1 "1" value causes OR gate 1808 to provide a logic "1" output
2 value, thereby maintaining pattern generator 1801 in a
3 cleared state. At this time, pattern generator 1801 provides
4 a trim signal t[9:0] having a value of zero. As a result,
5 the PS_TT[8:0] signal provided by up/down counter 1311 passes
6 through adder 1802 and pipeline register 1803 unchanged.
7 This effectively removes DSS circuit 1600 from delay lock
8 loop 400.

9 After delay lock loop 400 becomes locked, the
10 DLLS_LOCKED signal transitions to a logic high value. In
11 response, NAND gate 1809 provides a logic "0" output signal.
12 This logic "0" signal is latched into flip-flop 1805 on the
13 next rising edge of the PS_DLY_OUT signal. As a result, OR
14 gate 1808 provides a logic "0" signal which releases pattern
15 generator 1801, 5-bit up counter 1804 and flip-flop 1805. At
16 this time, pattern generator 1801 is enabled to generate a
17 predetermined pattern. The particular pattern is selected by
18 the SPREADSEL[3:0] signal. In one embodiment, pattern
19 generator 1801 is capable of generating patterns for creating
20 spread-2, spread-4, spread-6, spread-8, spread-16, spread-32,
21 and spread-64 configurations. In the present example, the
22 SPREADSEL[3:0] signal is selected to provide a pattern for a
23 spread-8 configuration.

24 In the described embodiment, up/down counter 1311
25 asserts a CHANGE_PS signal when the contents of up/down
26 counter 1311 are being changed. When the CHANGE_PS signal is
27 asserted, the output t[9:0] of pattern generator 1801 is
28 prevented from changing, thereby avoiding contention between
29 pattern generator 1801 and up/down counter 1311.

30 In general, pattern generator provides a trim value
31 t[9:0] to the A input terminal of adder 1802, and counter
32 1311 provides the PS_TT[8:0] signal to the B input terminal
33 of adder 1802. Note that a PS_TT[9] bit having a logic "0"
34 value is concatenated to the PS_TT[8:0] signal. Also note
35 that bits t[9:4] are set equal to t[3]. In the spread-8

1 pattern, the trim value $t[9:0]$ can have values of 0, +1, +2,
2 -1 and -2.

3 Adder 1802 performs a signed addition of the $PS_TT[9:0]$
4 and $t[9:0]$ signals, thereby providing a sum signal $s[9:0]$.
5 As long as the sum bit $s[9]$ has a logic "0" value, the sum
6 value $s[8:0]$ will be within the operating range of 512-tap
7 delay line 1304. The logic "0" sum bit $s[9]$ enables pipeline
8 register 1803 to latch the $s[8:0]$ signal. Pipeline register
9 1803 then transmits the $s[8:0]$ to binary-to-gray decoder 1305
10 as the $PS_TAP_TRIM[8:0]$ signal.

11 If sum bit $s[9]$ has a value of "1", then pipeline
12 register 1803 is disabled, and does not latch the
13 corresponding $s[8:0]$ signal. The logic "1" $s[9]$ bit is
14 clocked into flip-flop 1805 by the PS_DLY_OUT signal and
15 provided to the synchronous input terminal SI(6) of 5-bit up
16 counter 1804. When the PS_DLY_OUT signal is asserted high,
17 5-bit up counter 1804 is set to a value of "00110".

18 It should be noted that prior to loading counter 1804
19 with a value of "00110", counter 1804 was set to a value of
20 "10000". Bit [4] of the counter (i.e., the "1" bit in
21 "10000") is provided to inverter 1807. Inverter 1807, in
22 turn, provides a logic "0" bit the enable input (CE) of 5-bit
23 up counter 1804. As a result, the 5-bit up counter 1804 is
24 effectively disabled until it is loaded with the "00110"
25 value. The output of inverter 1807 is also used as a
26 $DSS_OVERFLOW$ signal.

27 After the "00110" value has been loaded into 5-bit up
28 counter 1804, bit [4] of the counter has a logic "0" state.
29 As a result, the $DSS_OVERFLOW$ signal is asserted high, and 5-
30 bit up counter 1804 is enabled. Once the $DSS_OVERFLOW$ signal
31 is set at a logic high state, this signal will remain in a
32 logic high state for at least 10 cycles of the PS_DLY_OUT
33 signal. The $DSS_OVERFLOW$ signal will be reset to a logic low
34 value if the $s[9]$ signal transitions back to a logic "0"
35 value, and remains at a logic "0" value for 10 consecutive
36 cycles of the PS_DLY_OUT signal. After the $s[9]$ signal

1 transitions to a logic "0" value, counter 1804 will begin
2 counting up. If the s[9] signal remains at a logic "0" state
3 for ten clock cycles, then counter 1804 will count up to
4 "10000", thereby clearing the DSS_OVERFLOW signal. However,
5 if the s[9] signal has a logic "1" value any time during
6 these ten clock cycles, then the 5-bit counter will be reset
7 to a "00110" value, thereby resulting in a logic high
8 DSS_OVERFLOW signal. This enables the user to reliably
9 sample the status of the DSS_OVERFLOW signal. (In the
10 described embodiment, the DSS_OVERFLOW signal is logically
11 OR'ed with the OVERFLOW signal of Fig. 15, thereby providing
12 a single signal to identify overflow conditions.)

13 The trim signals t[9:0] generated by pattern generator
14 1801 determine how the period of the PS_DLY_OUT signal is
15 adjusted. A spread-8 configuration will now be described.
16 This example assumes that the REF_CLK signal has a base
17 frequency of 100 MHz, and that the 512-tap/trim delay line
18 1304 is connected in line with the REF_CLK signal (i.e.,
19 S_LAGS_REF = 1 and CENTERED = 1). This example also assumes
20 that one trim delay is equal to 50 picoseconds (ps).

21 Figs. 19A-19B are waveform diagrams illustrating the
22 REF_CLK and S_CLK signals when DSS circuit 1600 is controlled
23 to implement a spread-8 configuration. During the first
24 three clock cycles C1-C3 (i.e., until 30000 ns) DSS circuit
25 1600 is disabled by the DSS_EN signal provided by the user.
26 As a result, pattern generator 1801 provides a trim signal
27 t[9:0] having a value of 0. During these three clock cycles
28 C1-C3, the REF_CLK and S_CLK are synchronized, with each of
29 these signals having a period of 10000 ns.

30 During the fourth clock cycle C4, pattern generator 1801
31 is enabled and provides a trim signal t[9:0] having a value
32 equal to 2 trim settings. In response, signed adder circuit
33 1802 provides adds two trim settings to the PS_TT[8:0] signal
34 provided by up/down counter 1311. As a result, the cycle C4
35 of the S_CLK signal is lengthened by two trim settings, or
36 100 ps. Cycle C4 of the S_CLK signal therefore has a period

1 of 10100 ns, such that the rising edge of the fifth cycle C5
2 of the S_CLK signal occurs at 40100 ns. At this time, there
3 is an initial offset of 100 ns between the REF_CLK and S_CLK
4 signals. This initial offset is provided one time only
5 before implementing the normal spread-8 configuration. This
6 initial offset enables the spread 8 configuration to be
7 implemented in an optimal manner as described below.

8 During the fifth clock cycle C5, pattern generator 1801
9 provides a trim signal t[9:0] having a value equal to 1 trim
10 setting. This represents a change of -1 trim setting (-50
11 ps) with respect to the previous cycle. As a result, the
12 S_CLK signal will have a period equal to 10000 ps - 50 ps, or
13 9950 ps, such that the rising edge of the next clock cycle C6
14 occurs at 50050 ns. The frequency of the S_CLK signal is
15 equal to 100.5 MHz during cycle C5.

16 During the sixth clock cycle C6, pattern generator 1801
17 provides a trim signal t[9:0] having a value equal to 2 trim
18 settings. This represents a change of +1 trim setting (+50
19 ps) with respect to the previous cycle. As a result, the
20 S_CLK signal will have a period equal to 10000 ps + 50 ps, or
21 10050 ps, such that the rising edge of the next clock cycle
22 C7 occurs at 60100 ns. The frequency of the S_CLK signal is
23 equal to 99.5 MHz during cycle C5.

24 Processing continues, with pattern generator 1801
25 providing trim signals t[9:0] having values of 0, 2, -1, 2, -
26 2, 2, and 2 during clock cycles C7-C13, respectively. These
27 trim values correspond with trim differences of -2, 2, -3, 3,
28 -4, 4 and 0 during clock cycles C7-C13, respectively. As a
29 result, the S_CLK signal has periods of 9900, 10100, 9850,
30 10150, 9800, 10200 and 10000 ps during clock cycles C7-C13,
31 respectively. This means that the S_CLK signal has
32 frequencies of 101, 99, 101.5, 98.5, 102, 98 and 100 MHz,
33 during clock cycles C7-C13, respectively. This provides for
34 each of the eight frequencies illustrated in Fig. 17B, plus
35 the base frequency of 100 MHz. The pattern of clock cycles

1 C5-C13 is repeated during the operation of delay lock loop
2 400, thereby continuing the spread spectrum operation.

3 In the example of Figs. 19A and 19B, the skew between
4 the REF_CLK signal and the S_CLK signal is equal to 50, 100,
5 0, 100, -50, 100, -100, 100 and 100 ps during clock cycles
6 C5-C13, respectively. Thus, the skew between these two
7 signals has a maximum value of 100 ps, and an average value
8 of 44.4 ps. This is a relatively stable clock signal in view
9 of the large number of frequencies provided.

10 In another embodiment of the present invention, the
11 initial offset provided during clock cycle C4 can be
12 eliminated. In this embodiment, the trim values provided by
13 pattern generator 1801 are selected to be -1, 0, -2, 0, -3,
14 0, -4, 0 and 0 during clock cycles C5-C13, respectively.
15 These trim values correspond with trim differences of -1, 1,
16 -2, 2, -3, 3, -4, 4 and 0 during clock cycles C5-C13,
17 respectively. As a result, the S_CLK signal has periods of
18 9950, 10050, 9900, 10100, 9850, 10150, 9800, 10200 and 10000
19 ps during clock cycles C5-C13, respectively. This means that
20 the S_CLK signal has frequencies of 100.5, 99.5, 101, 99,
21 101.5, 98.5, 102, 98 and 100 MHz, during clock cycles C5-C13,
22 respectively. Again, this provides for each of the eight
23 frequencies illustrated in Fig. 17B, plus the base frequency
24 of 100 MHz. The pattern of clock cycles C5-C13 is repeated
25 during the operation of delay lock loop 400, thereby
26 continuing the spread spectrum operation. In this example,
27 the skew between the REF_CLK signal and the S_CLK signal is
28 equal to -50, 0, -100, 0, -150, 0, -200, 0, and 0 ps,
29 respectively during clock cycles C5-C13, respectively. Thus,
30 the skew between these two signals has a maximum value of 200
31 ps, and an average value of -55.6 ps.

32 Although a spread-8 configuration (i.e., a base
33 frequency plus eight spread frequencies) has been described,
34 it is understood that other spread spectrum configurations
35 can also be implemented, and are considered to fall within

the scope of the present invention. For example, spread-2, spread-4 and spread-6 configurations can be provided. Pattern generator 1801 provides a pattern of trim values equal to -1, 0 and 0 to provide the three frequencies of the spread-2 configuration.

Pattern generator 1801 provides a pattern of trim values equal to -1, 0, -2, 0 and 0 to provide the five frequencies of the spread-4 configuration. To add an initial offset, pattern generator 1801 can provide a pattern of trim values equal to 1 (initial offset), 0, 1, -1, 1, and 1 to provide the five frequencies of the spread-4 configuration.

Pattern generator 1801 provides a pattern of trim values equal to -1, 0, -2, 0, -3, 0 and 0 to provide the seven frequencies of the spread-6 configuration. To add an initial offset, pattern generator 1801 can provide a pattern of trim values equal to 1 (initial offset), 0, 1, -1, 1, -2, 1 and 1 to provide the seven frequencies of the spread-6 configuration.

Table 1 below summarizes characteristics of spread-2, spread-4, spread-6 and spread-8 configurations for a 100 MHz base clock signal.

TABLE 1

DSS MODE	NONE	SPREAD-2	SPREAD-4	SPREAD-6	SPREAD-8
# of new freq.	0	2	4	6	8
Total # of freq.	1	3	5	7	9
% EMI peak reduction	0	67	80	86	89
+/- spread (trim units)	0	1	2	3	4
+/- spread (ps)	0	50	100	150	200

Table 2 below summarizes the +/- spread of the base clock signal for the various DSS modes for selected frequencies between 25 MHz and 400 MHz.

TABLE 2

Freq.	Period	+/- Spread (% of period)				
		NONE	SPRD-2	SPRD-4	SPRD-6	SPRD-8
25 MHz	40 ns	0.00%	0.13%	0.25%	0.38%	0.50%
50	20	0.00%	0.25%	0.50%	0.75%	1.00%
100	10	0.00%	0.50%	1.00%	1.50%	2.00%
200	5	0.00%	1.00%	2.00%	3.00%	4.00%
400	2.5	0.00%	2.00%	4.00%	6.00%	8.00%

Table 3 below summarizes the number of ideal peaks within a 1 MHz window for the various DSS modes for selected frequencies between 25 MHz and 400 MHz.

TABLE 3

Freq.	Period	# IDEAL PEAKS INSIDE 1 MHZ WINDOW				
		NONE	SPRD-2	SPRD-4	SPRD-6	SPRD-8
25 MHz	40 ns	1	3	5	7	9
50	20	1	3	5	7	9
100	10	1	3	3	3	3
200	5	1	1	1	1	1
400	2.5	1	1	1	1	1

Table 4 below summarizes the percentage of EMI energy reduction within a 1 MHz window for the various DSS modes for selected frequencies between 25 MHz and 400 MHz.

TABLE 4

Freq.	Period	+/- Spread (% of period)				
		NONE	SPRD-2	SPRD-4	SPRD-6	SPRD-8
25 MHz	40 ns	0%	0%	0%	0%	0%
50	20	0%	0%	0%	0%	0%
100	10	0%	0%	40%	57%	67%
200	5	0%	67%	80%	86%	89%
400	2.5	0%	67%	80%	86%	89%

Table 5 below summarizes the EMI energy reduction within a 1 MHz window in db for the various DSS modes for selected frequencies between 25 MHz and 400 MHz.

TABLE 5

Freq.	Period	1 MHZ EMI ENERGY REDUCTION (db)				
		NONE	SPRD-2	SPRD-4	SPRD-6	SPRD-8
25 MHz	40 ns	0	0	0	0	0
50	20	0	0	0	0	0
100	10	0	0	-2.2	-3.7	-4.8
200	5	0	-4.8	-7.0	-8.5	-9.5
400	2.5	0	-4.8	-7.0	-8.5	-9.5

Table 6 below summarizes the 1 MHz window range for selected frequencies between 25 MHz and 400 MHz.

TABLE 6

Frequency (MHz)	Period (ns)	1 MHz Window Range (period)
25	40	39.22 to 40.82 ns
50	20	19.80 to 20.20 ns
100	10	9.95 to 10.05 ns
200	5	4.99 to 5.01 ns
400	2.5	2.497 to 2.503 ns

Although the invention has been described in connection with several embodiments, it is understood that this invention is not limited to the embodiments disclosed, but is capable of various modifications which would be apparent to a person skilled in the art. For example, in view of this disclosure those skilled in the art can define other clock phase shifters, delay lines, output generators, controllers, phase detectors, and so forth, and use these alternative features to create a method, circuit, or system according to the principles of this invention. Thus, the invention is limited only by the following claims.

APPENDIX A

APPENDIX A CORRESPONDING TERMINOLOGY
TERMINOLOGY USED IN THE SPECIFICATION

DLL	Delay Lock Loop 400
ZD2 section	Clock Phase Shifter 350
PS section	Digital Phase Shifter 1100
ZD1 section	Delay Line 310

ResetZD2	Reset Clock Phase Shifter 350
ResetPS	Reset Digital Phase Shifter 1100
ResetZD1	Reset Delay Line 310
ChangeZD2	When asserted, allows Clock Phase Shifter 350 to make a tap/trim change
GoPS	GO (when asserted, allows Digital Phase Shifter to make a tap/trim change)
ChangeZD1	When asserted, allows Delay Line 310 to make a tap/trim change
DLL_locked	DLL_LOCKED
locked_pre	Similar to DLL_LOCKED, except it remains true even if overflow occurs
PSlocked	When asserted, indicates that the initial tap/trim for delay line 1304 has been set
FREEZEDLL	User signal that holds all updates to delay lines in Delay Lock Loop 400
EnZD2	Configuration bit that enables Clock Phase Shifter 350 (allows ResetZD2 to go inactive)
EnPS	Configuration bit that enables Digital Phase Shifter 1100 (allows ResetPS to go inactive)
EnZD1	Configuration bit that enables Delay Line 310 (allows Reset ResetZD1 to go inactive)

CTLMODE	When true, DLL 400 is in test mode
Z2locked	When asserted, indicates that Clock Phase Shifter 350 delay lines have been adjusted (i.e., total delay is one CLKIN period)
DonePS	DONE
Z1locked	When asserted, indicates that Delay line 310 has been adjusted (i.e., PS_S_CLK and PS_REF_CLK are in phase)
ZD2overflow	When asserted, indicates a wrap attempt on one or more delay line sections in Clock Phase Shifter 350
ZD1overflow	When asserted, indicates a wrap attempt on Delay Line 310
Clk	REF_CLK

```

/*****
*
*   File Name:   DLLmngt_9 v
*   Version:    snapshot_00 08.07revA
*   Generated:   Tue Sep 26 17:15:26 2000 (Pacific Time)
*
*   Author:     John Logue
*   Email:      john.logue@xilinx.com
*   Company:    Xilinx
*
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*               All rights reserved
*
*****/

`timescale 1 ps / 1 ps

module DLLmngt_9(
    ResetZD2, ResetPS, ResetZD1,
    ChangeZD2, GoPS, ChangeZD1,
    DLL_locked, locked_pre,
    PSlocked, FREEZEDLL, EnZD2, EnPS, EnZD1, CTLMODE,
    DeadTime, LiveTime, z2Locked, DonePS, z1Locked,
    ZD2overflow,
    // PSoverflow,
    ZD1overflow,
    Clk, Reset);

// This is a one-hot state machine that controls modules zd2Synth, PhaseShift,
// and zd1Synth.
// It has the following configuration:
//   Timeout counter width in bits: 9

// FREEZEDLL operation:

// If FREEZEDLL_S goes true when in a state between updates (deadtime), that
// state is retained until FREEZEDLL_S goes false; i.e., it hangs in that state
// until FREEZEDLL_S goes false.

// If FREEZEDLL_S goes true when updating PS, nothing happens until it advances
// to the next deadtime state, where it hangs until FREEZEDLL_S goes false.

// If FREEZEDLL_S goes true when updating ZD1 or ZD2, it immediately exits to
// the corresponding deadtime state, where it hangs until FREEZEDLL_S goes
// false.

output ResetZD2;    // ZD2 reset
output ResetPS;     // PhaseShift reset
output ResetZD1;    // ZD1 reset
output ChangeZD2;    // Allow ZD2 to make a tap/trim change
output GoPS;         // Go signal to PhaseShift
output ChangeZD1;    // Allow ZD1 to make a tap/trim change
output DLL_locked;   // DLL top level locked status
output locked_pre;   // locked status that remains true if overflow occurs

```

```

input  PSlocked;        // The initial Phase Shift tap/trim has been set
input  FREEZEDLL;       // Halts all DLL delay line updates as soon as possible
input  EnZD2;           // config bit.  ZD2 enabled
input  EnPS;            // config bit:  PhaseShift enabled
input  EnZD1;           // config bit:  ZD1 enabled
input  CTLMODE;         // true when test mode selected
input  [7:0] DeadTime;   // init value for Timeout cntr between module enables
input  [7:0] LiveTime;   // init value for Timeout cntr during ZD2 & ZD1 enables
input  z2Locked;        // ZD2 is locked
input  DonePS;          // Done signal from PhaseShift
input  z1Locked;        // ZD1 locked
input  ZD2overflow;     // Wrap attempt on one or more ZD2 delay lines
input  ZD1overflow;     // Wrap attempt on ZD1 delay line

input  Clk;
input  Reset;           // asynchronous reset

// ***** DLL Locked *****

// DLL_locked goes true when all selected functions are locked.
// Overflow on ZD1 or ZD2 causes it to go false (if the function is selected).
// It is always true if no functions are selected.
assign DLL_locked = (~EnZD2 | (z2Locked & ~ZD2overflow))
                   & (~EnPS | (PSlocked))
                   & (~EnZD1 | (z1Locked & ~ZD1overflow));

// locked_pre is an SR latch that remembers the 1st DLL_locked after Reset
assign locked_pre = ~(Reset | ~(DLL_locked | locked_pre));

// ***** Synchronizers *****

reg z2Locked_S;
always @(posedge Clk) z2Locked_S  <= #`FFDLY z2Locked;

reg DonePS_S;
always @(posedge Clk) DonePS_S    <= #`FFDLY DonePS;

reg z1Locked_S;
always @(posedge Clk) z1Locked_S  <= #`FFDLY z1Locked;

reg FREEZEDLL_S;
always @(posedge Clk) FREEZEDLL_S <= #`FFDLY FREEZEDLL;

// ***** State Machine Parameters *****

// define state bit numbers
parameter IDLE      = 0, // 001 Must be bit 0 (State is Reset to 1)
          INITPS    = 1, // 002 initialize PhaseShift
          INITZD1   = 2, // 004 initialize ZD1
          WDZD2     = 3, // 008 wait dead time before changing ZD2
          WLZD2     = 4, // 010 wait live time while changing ZD2
          WDPS      = 5, // 020 wait dead time before changing PhaseShift
          WDONE     = 6, // 040 wait PhaseShift Done
          WDZD1     = 7, // 080 wait dead time before changing ZD1
          WLZD1     = 8; // 100 wait live time while changing ZD1

reg [WLZD1:0] State;      // Current state

```

```

reg [WLZD1:0] NextState; // next state

assign ChangeZD2 = State[IDLE] | State[WLZD2];
assign ChangeZD1 = State[INITZD1] | State[WLZD1];
assign GoPS      = State[INITPS] | State[WDONE];

// ***** Resets *****

// This section generates reset signals for ZD2, PS, ZD1, and the DLLmngr
// itself. All resets go active while Reset is true. The various resets
// then go inactive (or not) as follows:

// ResetZD2 - goes inactive immediately if EnZD2 is true; otherwise,
//            it never goes inactive.

// ResetPS - goes inactive immediately if EnPS & CTLMODE are both true, else
//            goes inactive when ZD2 locks, if EnPS is true; otherwise,
//            it never goes inactive.

// ResetZD1 - goes inactive immediately if EnZD1 & CTLMODE are both true;
//            otherwise, it goes inactive synchronous to the rising edge of
//            Clk when signal RelResetZD1 is true.

// DLLmngrReset - goes inactive immediately if any of ZD2, PS, or ZD1 are
//                enabled AND Test Mode is not selected. Otherwise, it
//                never goes inactive.

wire ResetZD2n = ~(Reset | ~(ResetZD2n | EnZD2)); // SR latch
wire ResetZD2  = ~ResetZD2n;

wire ClrResetPS = EnPS & (z2Locked | CTLMODE); // JDL 07/31/00

wire ResetPSn = ~(Reset | ~(ResetPSn | ClrResetPS)); // SR latch JDL
07/24/00
wire ResetPS  = ~ResetPSn;

wire RelResetZD1 = State[INITPS] & EnZD1 & (~EnPS | DonePS_S);

wire AsyncClr = EnZD1 & CTLMODE;
reg ResetZD1;
always @(posedge Clk or posedge Reset or posedge AsyncClr)
begin
    if (Reset)      ResetZD1 <= #`FFDLY 1'b1; // async set
    else if (AsyncClr) ResetZD1 <= #`FFDLY 1'b0; // async clr
    else if (RelResetZD1) ResetZD1 <= #`FFDLY 1'b0; // edge trigger
end

wire EnDLLmngr = (EnZD2 | EnPS | EnZD1) & ~CTLMODE;

wire DLLmngrResetN = ~(Reset | ~(DLLmngrResetN | EnDLLmngr)); // SR latch
wire DLLmngrReset  = ~DLLmngrResetN;

// ***** TimeOut Counter *****

wire SelLive = State[WDZD2] | State[WDPS] | State[WDZD1];

wire [7:0] TOcntrMux = SelLive ? LiveTime : DeadTime;

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wire [8:0] TOcntr;
wire TO = TOcntr[8]; // timeout

wire LdTOcntr = State[INITZD1]
               | (State[WDZD2] & TO)
               | (State[WLZD2] & TO)
               | (State[WDPS] & TO)
               | State[WDONE]
               | (State[WDZD1] & TO)
               | (State[WLZD1] & TO);

// instantiate timeout counter
cntr_9_AI_0_LD_CE_DN TOC(
    .Out(TOcntr),
    .AI(DLLmngReset),
    .LD(LdTOcntr),
    .In({1'b0, TOcntrMux}),
    .CE(~TO),
    .Clk(Clk));

// ***** State Machine *****

always @(posedge Clk or posedge DLLmngReset)
    if (DLLmngReset) State <= #`FFDLY 1; // select IDLE state on Reset
    else State <= #`FFDLY NextState;

// next state network
always @(State or EnZD1 or EnZD2 or EnPS or
    z2Locked_S or DonePS_S or z1Locked_S or TO or FREEZEDLL_S)
begin
    NextState = 0;

    case(1'b1) // synopsys parallel_case full_case
        State[IDLE] : begin // idle
            if (EnZD2 & ~z2Locked_S) NextState[IDLE] = 1'b1;
            else NextState[INITPS] = 1'b1;
        end
        State[INITPS] : begin // initialize PhaseShift
            if (EnPS & ~DonePS_S) NextState[INITPS] = 1'b1;
            else NextState[INITZD1] = 1'b1;
        end
        State[INITZD1] : begin // initialize ZD1
            if (EnZD1 & ~z1Locked_S)
            begin
                NextState[INITZD1] = 1'b1;
            end
            else
            begin
                if (EnZD2) NextState[WDZD2] = 1'b1;
                else NextState[WDZD1] = 1'b1;
            end
        end
        State[WDZD2] : begin // wait dead time before changing ZD2
            if (~TO | FREEZEDLL_S) NextState[WDZD2] = 1'b1;
            else NextState[WLZD2] = 1'b1;
        end
    endcase
end

```

```

State[WLZD2]   : begin // wait live time while changing ZD2
                  if(~TO & ~FREEZEDLL_S)      NextState[WLZD2] = 1'b1;
                  else if (FREEZEDLL_S) NextState[WDZD2] = 1'b1;
                  else if (EnPS)      NextState[WDPS] = 1'b1;
                  else if (EnZD1)     NextState[WDZD1] = 1'b1;
                  else                 NextState[WDZD2] = 1'b1;
                end
State[WDPS]    : begin // wait dead time before changing PhaseShift
                  if(~TO | FREEZEDLL_S) NextState[WDPS] = 1'b1;
                  else NextState[WDONE] = 1'b1;
                end
State[WDONE]   : begin // wait PhaseShift Done
                  if(~DonePS_S) NextState[WDONE] = 1'b1;
                  else if (EnZD1) NextState[WDZD1] = 1'b1;
                  else NextState[WDZD2] = 1'b1;
                end
State[WDZD1]   : begin // wait dead time before changing ZD1
                  if(~TO | FREEZEDLL_S) NextState[WDZD1] = 1'b1;
                  else NextState[WLZD1] = 1'b1;
                end
State[WLZD1]   : begin // wait live time while changing ZD1
                  if(~TO & ~FREEZEDLL_S)      NextState[WLZD1] = 1'b1;
                  else if (FREEZEDLL_S) NextState[WDZD1] = 1'b1;
                  else if (EnZD2)      NextState[WDZD2] = 1'b1;
                  else                 NextState[WDZD1] = 1'b1;
                end
                end
default       : begin
                  NextState = 9'bx;
                end
            endcase
        end
    endmodule

```

DLL Manager

Overview

This is the master control module for the DLL. It performs the following functions:

1. Sequences the Reset signals to the ZD2, PS, and ZD1 sections.
2. Ensures that the sections initialize (lock) in the proper sequence (ZD2, PS, ZD1).
3. Ensures that clock cycles that are shortened or lengthened due to a trim change are not sampled by the phase detector of another DLL section. This is done by allowing only one section to change trims at a given time, and inserting a no activity time between each allowed change.
4. Generates DLL_locked signal.

FREEZEDLL Notes

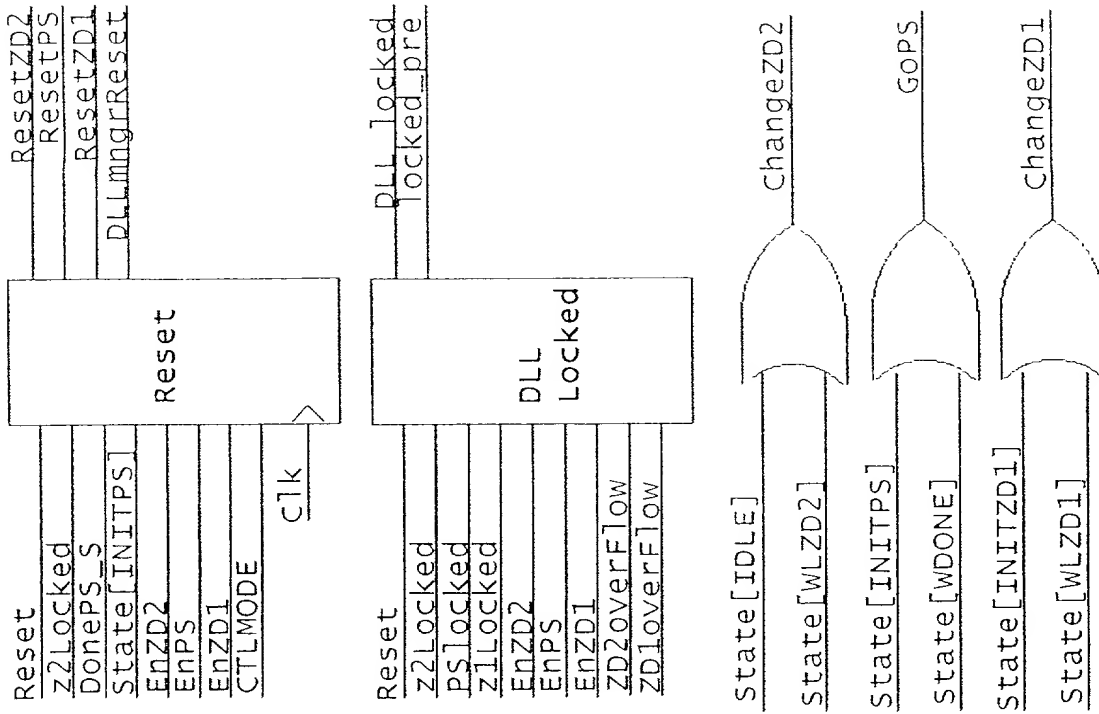
If FREEZEDLL_S goes true when in a state between updates (deadtime), that state is retained until FREEZEDLL_S goes false; i.e., it hangs in that state until FREEZEDLL_S goes false.

If FREEZEDLL_S goes true when updating PS, nothing happens until it advances to the next deadtime state, where it hangs until FREEZEDLL_S goes false.

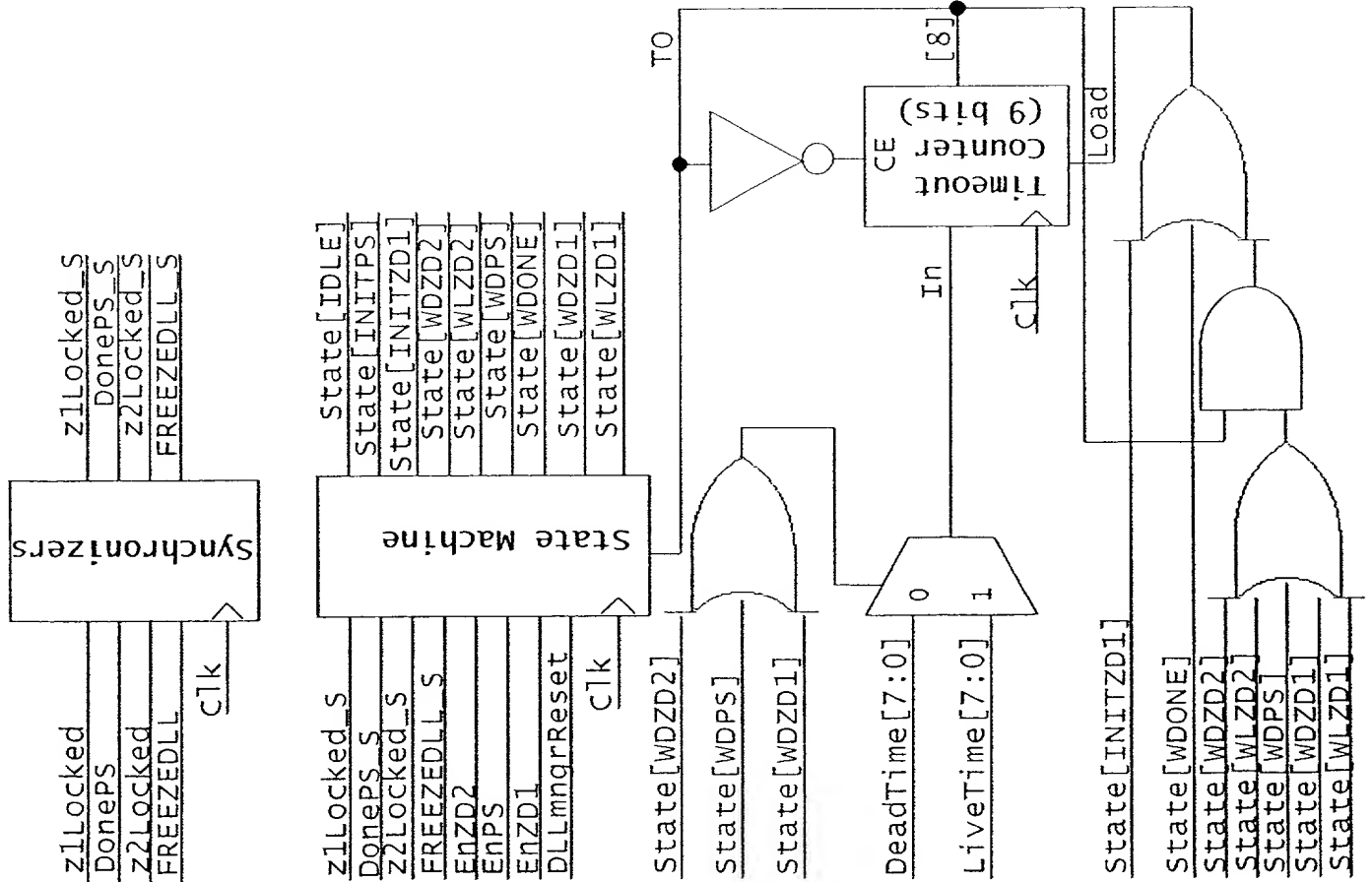
If FREEZEDLL_S goes true when updating ZD1 or ZD2, it immediately exits to the corresponding deadtime state, where it hangs until FREEZEDLL_S goes// false.

Input & Output Pins

Outputs	
ResetZD2	ZD2 reset
ResetPS	Phaseshift reset
ResetZD1	ZD1 reset
ChangeZD2	Allow ZD2 to make a tap/trim change
GoPS	Go signal to Phaseshift
ChangeZD1	Allow ZD1 to make a tap/trim change
DLL_locked	DLL top level locked status
Locked_pre	Locked status that remains true if overflow occurs
Inputs	
PSlocked	The initial Phase shift tap/trim has been set
FREEZEDLL	Halts all DLL delay line updates as soon as possible
EnZD2	config bit: ZD2 enabled
EnPS	config bit: Phaseshift enabled
EnZD1	config bit: ZD1 enabled
CTLMODE	true when test mode selected
DeadTime [7:0]	init value for Timeout cntr between module enables
LiveTime [7:0]	init value for Timeout cntr during ZD2 & ZD1 enables
z2Locked	ZD2 is locked
DonePS	Done signal from Phaseshift
z1Locked	ZD1 Locked
ZD2overflow	wrap attempt on one or more ZD2 delay lines
ZD1overflow	wrap attempt on ZD1 delay line
Reset	Asynchronous DCM Reset (RST)
clk	Connected to DCM input clock (CLKIN)



Block Diagram



Reset Notes

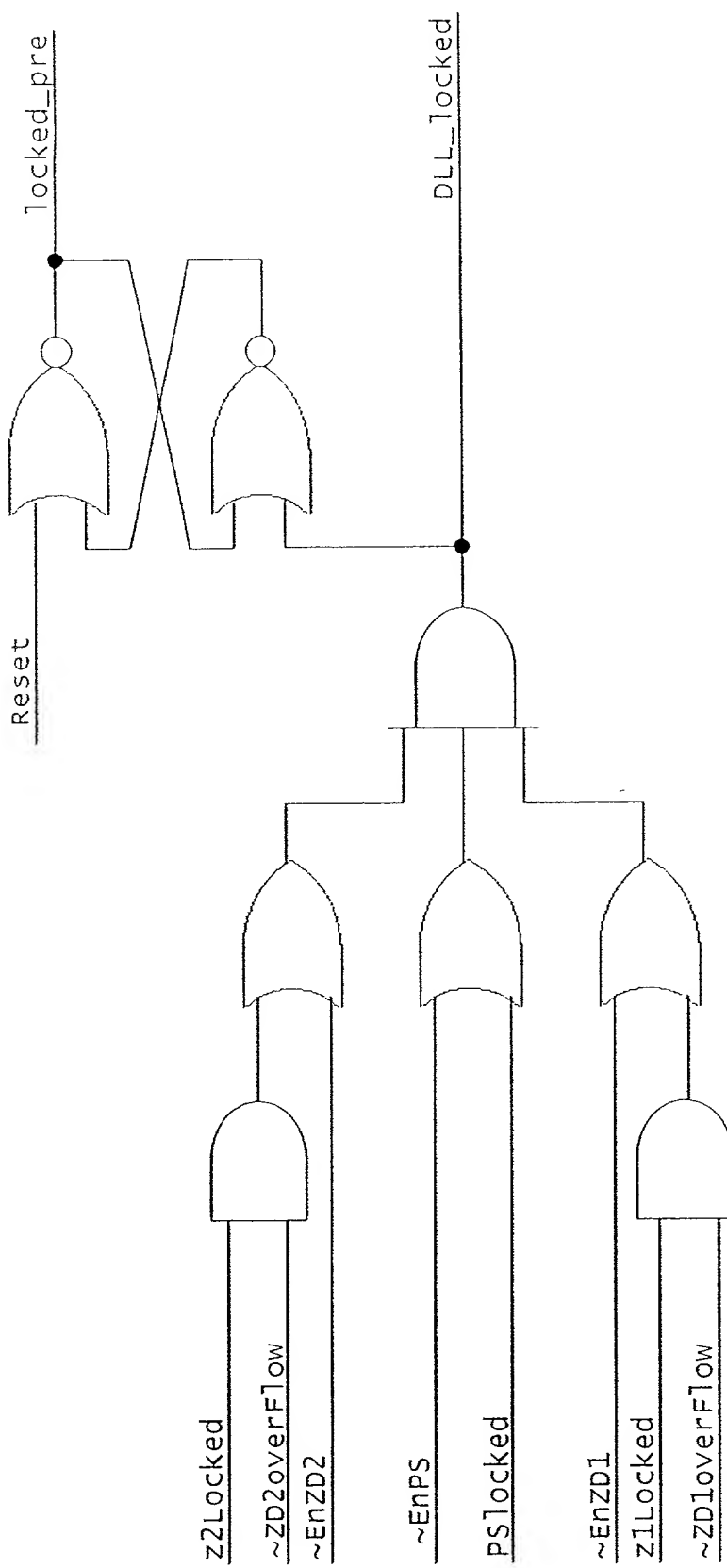
This section generates reset signals for ZD2, PS, ZD1, and the DLLmngnr itself. All resets go active while Reset is true. The various resets then go inactive (or not) as follows:

ResetZD2 - goes inactive immediately if EnZD2 is true; otherwise, it never goes inactive.

ResetPS - goes inactive immediately if EnPS & CTLMODE are both true, else goes inactive when ZD2 locks, if EnPS is true; otherwise, it never goes inactive.

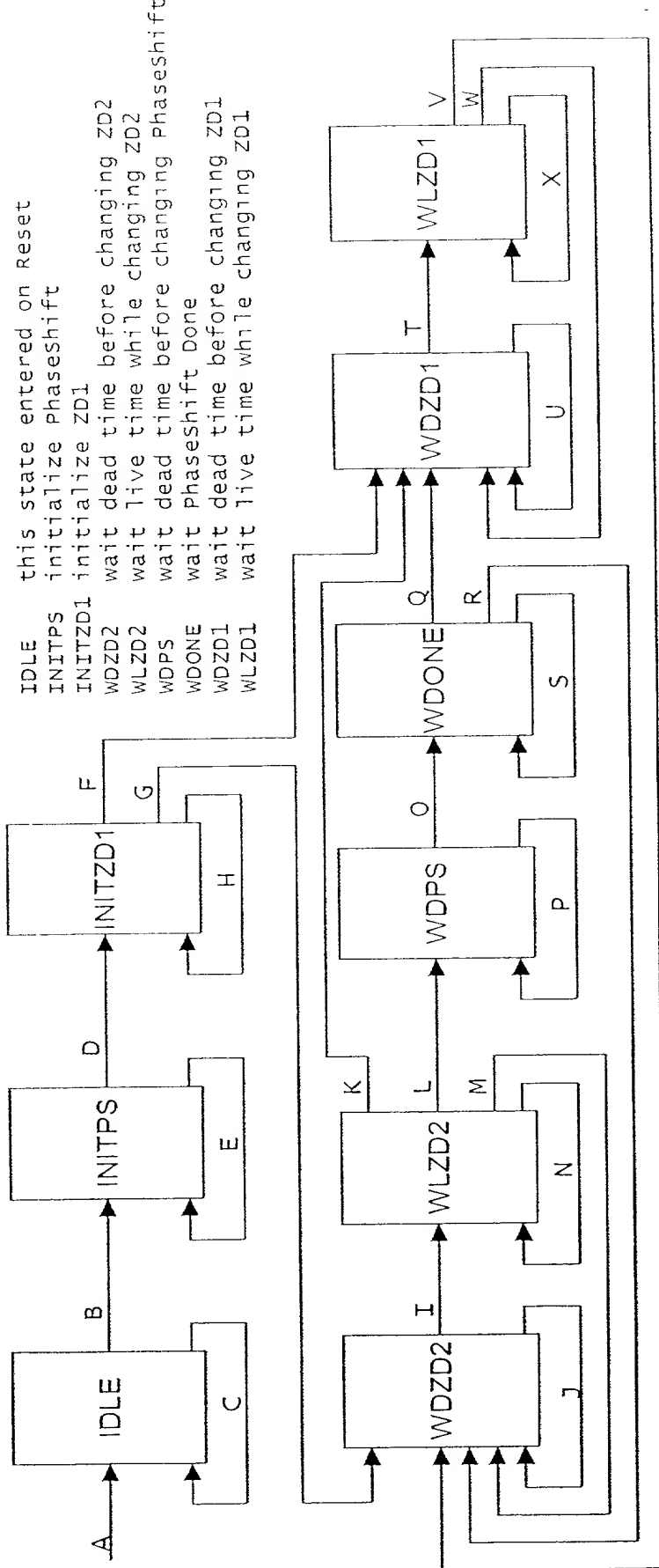
ResetZD1 - goes inactive immediately if EnZD1 & CTLMODE are both true; otherwise, it goes inactive synchronous to the rising edge of Clk when signal ReResetZD1 is true.

DLLmngnrReset - goes inactive immediately if any of ZD2, PS, or ZD1 are enabled AND Test Mode is not selected. Otherwise, it never goes inactive.



`DLL_locked` goes true when all selected functions are Locked. overflow on `ZD1` or `ZD2` causes it to go false (if the function is selected). It is always true if no functions are selected.

DLL Locked



Conditions

- A DLLmngReset
- B ~C
- C EnZD2 & ~z2Locked_s
- D ~E
- E EnPS & ~DonePS_s
- F ~H & ~EnZD2
- G ~H & EnZD2
- H EnZD1 & ~z1Locked_s
- I ~J
- J ~TO & ~FREEZEDLL_s
- K TO & ~FREEZEDLL_s & ~EnPS & EnZD1
- L TO & ~FREEZEDLL_s & EnPS
- M FREEZEDLL_s | (TO & ~EnPS & ~EnZD1)
- N ~TO & ~FREEZEDLL_s

- O ~P
- P ~TO | FREEZEDLL_s
- Q DonePS_s & EnZD1
- R DonePS_s & ~EnZD1
- S ~DonePS_s
- T ~U
- U ~TO | FREEZEDLL_s
- V TO & ~FREEZEDLL_s & EnZD2
- W FREEZEDLL_s
- X ~TO & ~FREEZEDLL_s

State Machine

CLAIMS

We Claim:

1. A method for spreading the electromagnetic emissions of a generated clock that is created in response to a reference clock signal, the method comprising the steps of:

providing an adjustable delay line having a plurality of selectable delay trim units in the path of the reference clock signal;

enabling a first set of delay trim units in the adjustable delay line during a first clock period, thereby causing the generated clock signal to exhibit a first clock period;

enabling a second set of delay trim units in the adjustable delay line during a second clock period, thereby causing the generated clock signal to exhibit a second clock period, wherein the second clock period is less than the first clock period; and

enabling a third set of delay trim units in the adjustable delay line during a third clock period, thereby causing the generated clock signal to exhibit a third clock period, wherein the third clock period is greater than the first clock period.

2. The method of Claim 1, further comprising the steps of:

enabling a fourth set of delay trim units in the adjustable delay line during a fourth clock period, thereby causing the generated clock signal to exhibit a fourth clock period, wherein the fourth clock period is less than the second clock period; and

enabling a fifth set of delay trim units in the adjustable delay line during a fifth clock period, thereby causing the generated clock signal to exhibit a fifth clock period, wherein the fifth clock period is greater than the third clock period.

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3. The method of Claim 1, wherein a difference between the first clock period and the second clock period is about 50 picoseconds or more.

4. The method of Claim 3, wherein a difference between the first clock period and the third clock period is about 50 picoseconds or more.

5. The method of Claim 1, further comprising the step of adjusting the delay trim units in the adjustable delay line in a predetermined pattern.

6. The method of Claim 1, further comprising the step of generating an overflow signal if the delay trim units enabled in the adjustable delay line reach a predetermined level.

7. A method for spreading the electromagnetic emissions of a generated clock that is created in response to a reference clock signal, the method comprising the steps of:

providing an adjustable delay line having a plurality of selectable delay trim units in the path of the reference clock signal;

generating a first control signal for enabling a first set of delay trim units in the adjustable delay line, the first set of delay trim units being selected to provide a generated clock signal having a base clock period;

generating a second control signal for adjusting the first set of delay trim units, the second control signal being selected to vary in a predetermined pattern;

combining the first control signal and the second control signal to create a third control signal;

1 providing the third control signal to the
2 adjustable delay line, wherein the third control signal
3 causes different sets of delay trim units to be enabled
4 during different cycles of the reference clock signal,
5 thereby causing the generated clock signal to exhibit a
6 pattern of varying clock periods, wherein the pattern of
7 clock periods includes the base clock period, as well as
8 clock periods greater than and less than the base clock
9 period.

10
11 8. A method for spreading the electromagnetic emissions
12 of a generated clock signal that is created in response to a
13 reference clock signal, the method comprising the steps of:

14 providing a delay line in the path of the reference
15 clock signal; and

16 adjusting the trim units in the delay line in a
17 pre-determined pattern during consecutive clock cycles.

18
19 9. The method of Claim 8, further comprising the step
20 of providing an offset in the reference clock signal prior to
21 the step of adjusting.

22
23 10. The method of Claim 9, wherein the step of
24 providing an offset comprises providing a trim unit
25 adjustment of +2 prior to starting the pattern and wherein
26 the pattern comprises providing trim unit adjustments of +1,
27 +2, 0, +2, -1, +2, -2, +2 and +2 during nine consecutive
28 clock cycles.

29
30 11. The method of Claim 8, wherein the pattern
31 comprises providing trim unit adjustments of -1, 0, -2, 0,
32 -3, 0, -4, 0 and 0 during nine consecutive clock cycles.

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34 12. The method of Claim 8, wherein the pattern
35 comprises providing trim unit adjustments of -1, 0 and 0
36 during three consecutive clock cycles.

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13. The method of Claim 8, wherein the pattern comprises providing trim unit adjustments of -1, 0, -2, 0 and 0 during five consecutive clock cycles.

14. The method of Claim 9, wherein the step of providing an offset comprises providing a trim unit adjustment of +1 prior to starting the pattern, and wherein the pattern comprises providing trim unit adjustments of 0, +1, -1, +1 and +1 during five consecutive clock cycles.

15. The method of Claim 8, wherein the pattern comprises providing trim unit adjustments of -1, 0, -2, 0, -3, 0 and 0 during seven consecutive clock cycles.

16. The method of Claim 9, wherein the step of providing an offset comprises providing a trim unit adjustment of +1 prior to starting the pattern, wherein the pattern comprises providing trim unit adjustments of 0, +1, -1, +1, -2, +1 and +1 during seven consecutive clock cycles.

17. The method of Claim 8, wherein the clock signal exhibits different frequencies during successive cycles, the energy of the clock signal being spread equally over the different frequencies.

18. The method of Claim 9, wherein the offset is selected to minimize the worst-case skew introduced between the reference clock signal and the generated clock signal.

DIGITAL SPREAD SPECTRUM CIRCUITRY

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ABSTRACT

The frequency of a skew clock signal is dithered around a base frequency, thereby enabling this clock signal to comply with FCC requirements for electromagnetic emissions within a specified window (e.g., a 1 MHz window). That is, delay can be introduced such that the clock signals exhibit slightly different frequencies in successive periods. For example, the frequency of a 100 MHz clock signal can be adjusted to have frequencies of approximately 98, 98.5, 99, 99.5, 100, 100.5, 101, 101.5, and 102 MHz during different periods. This configuration is referred to as a spread-8 configuration, because eight frequencies are used in addition to the base frequency of 100 MHz. Because the frequencies are spread in 0.5 MHz increments, only three of the nine frequencies are included in any 1 MHz window. As a result, 2/3 of the energy of the clock signal is not included when determining whether the clock signal meets the FCC electromagnetic emission requirements in this test. By spreading the frequencies above and below the base frequency in a regular manner, the average frequency of the clock signal becomes equal to the base frequency. Other configurations including, but not limited to, spread-2, spread-4, spread-6, spread-16 and spread-32 configurations, can also be implemented.

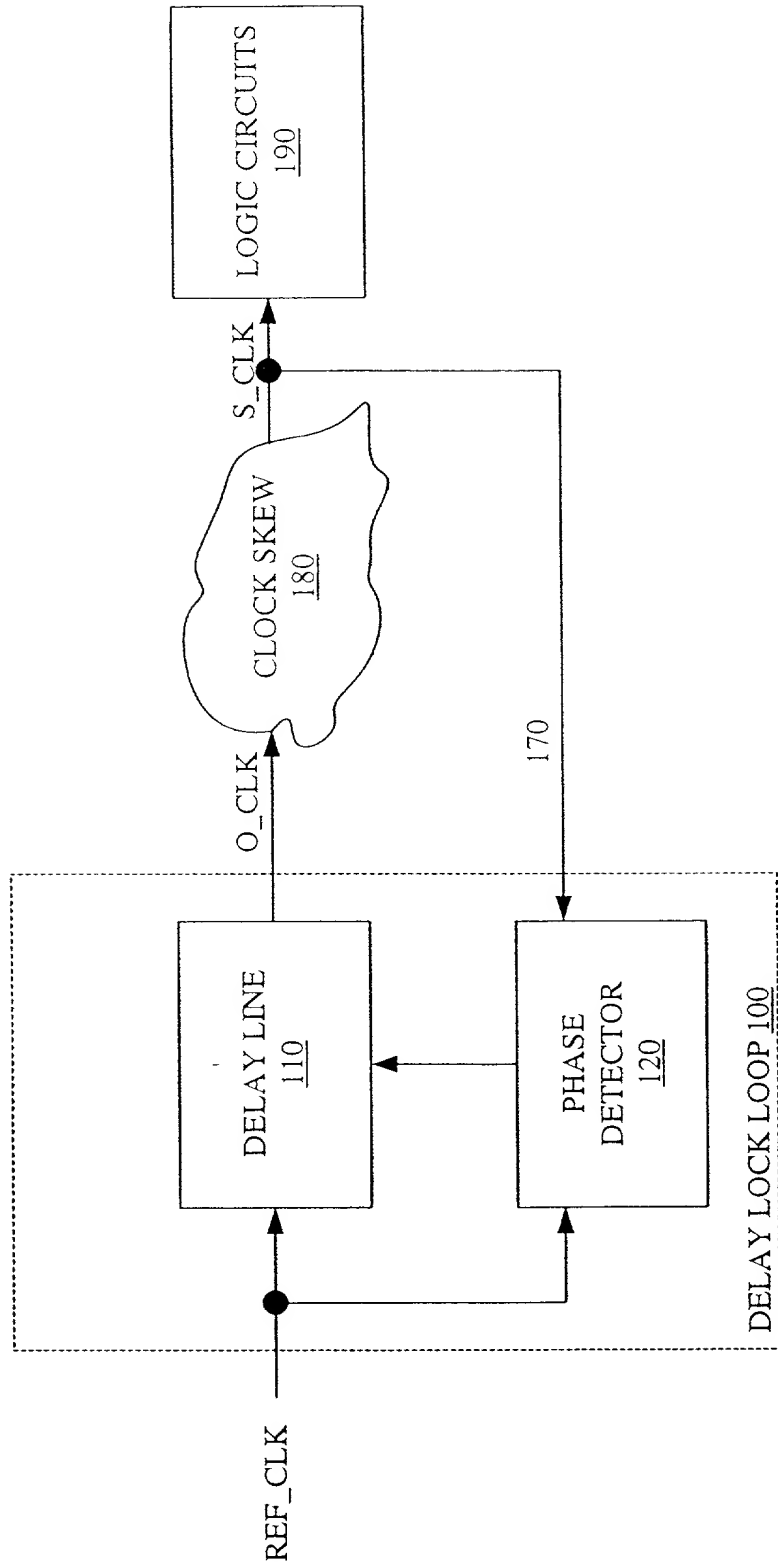


FIGURE 1 (Prior Art)

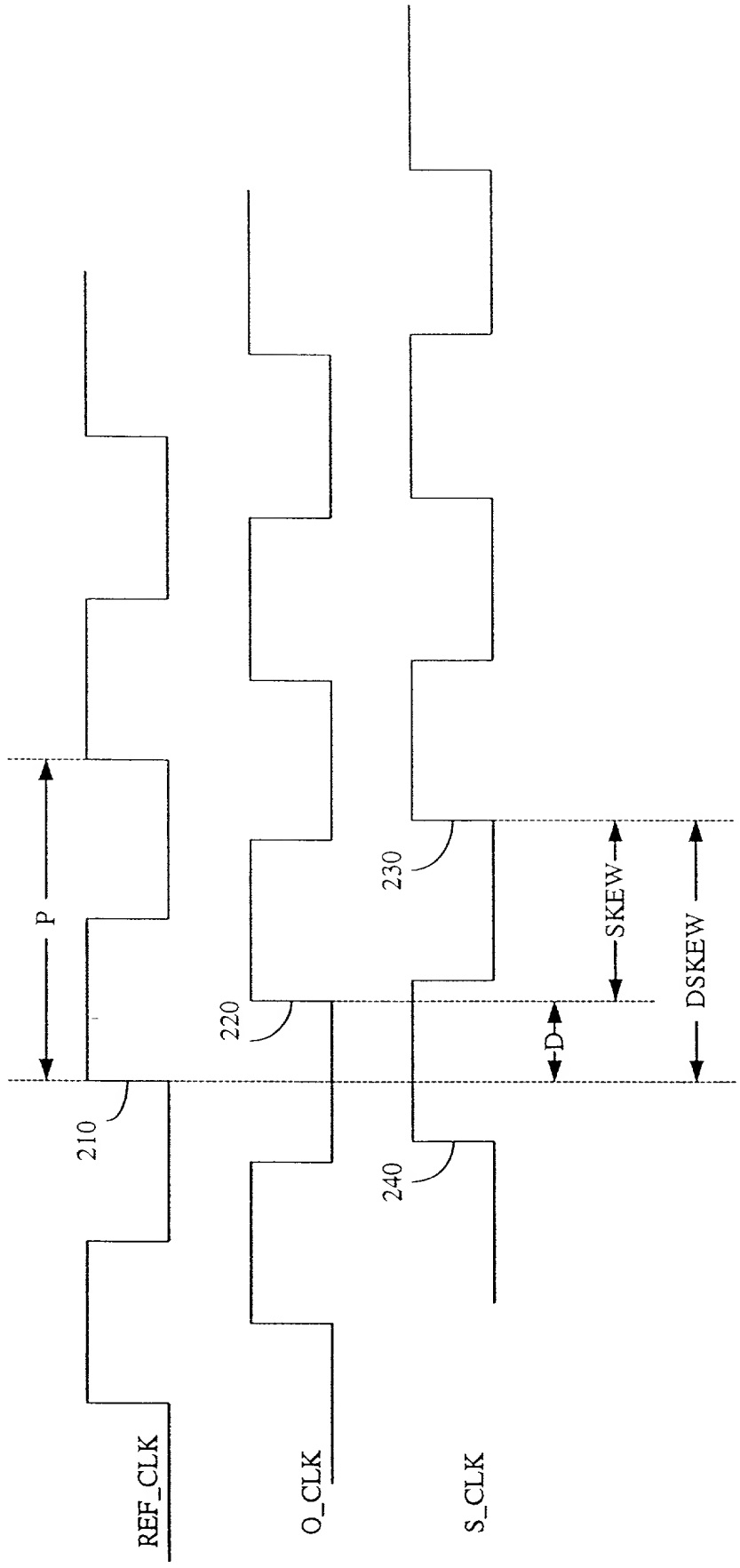


FIGURE 2A

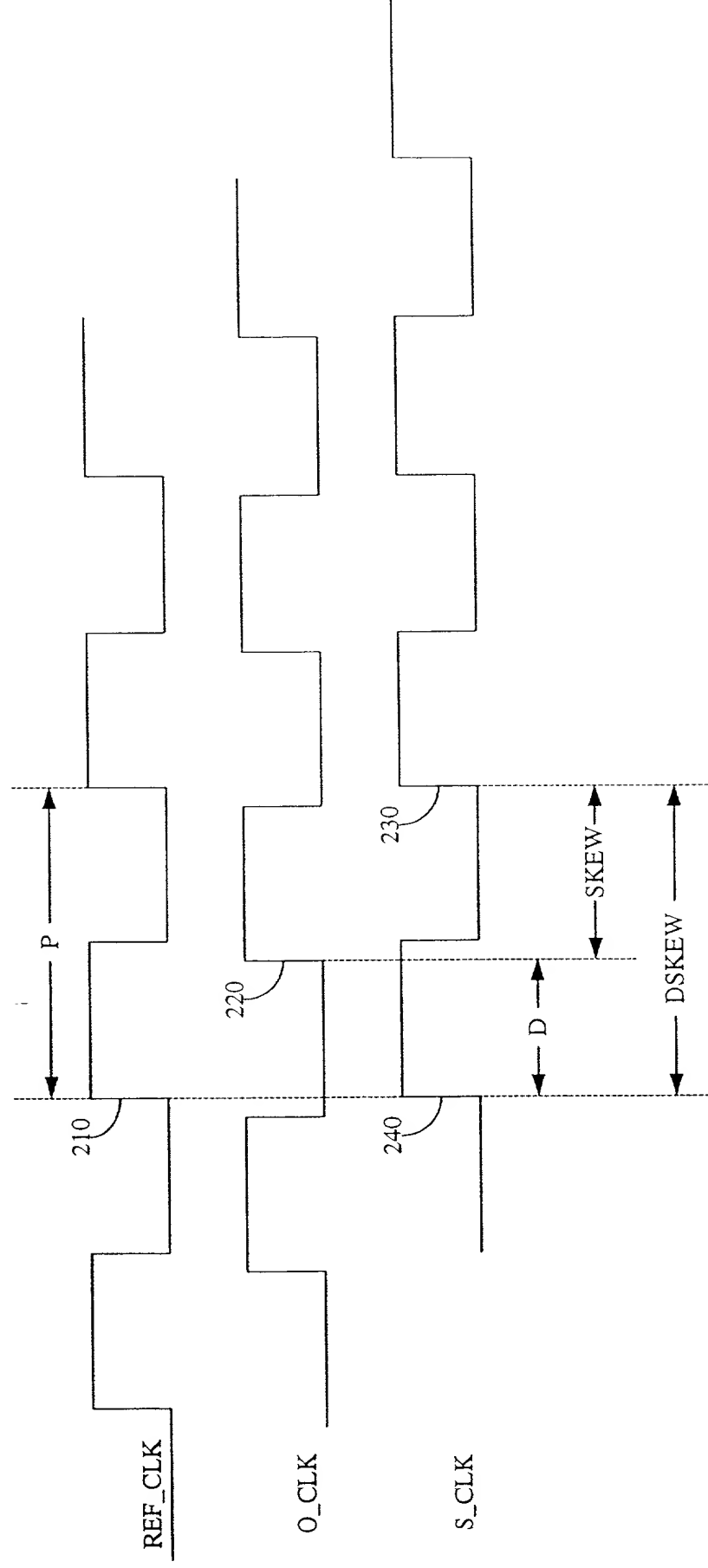


FIGURE 2B

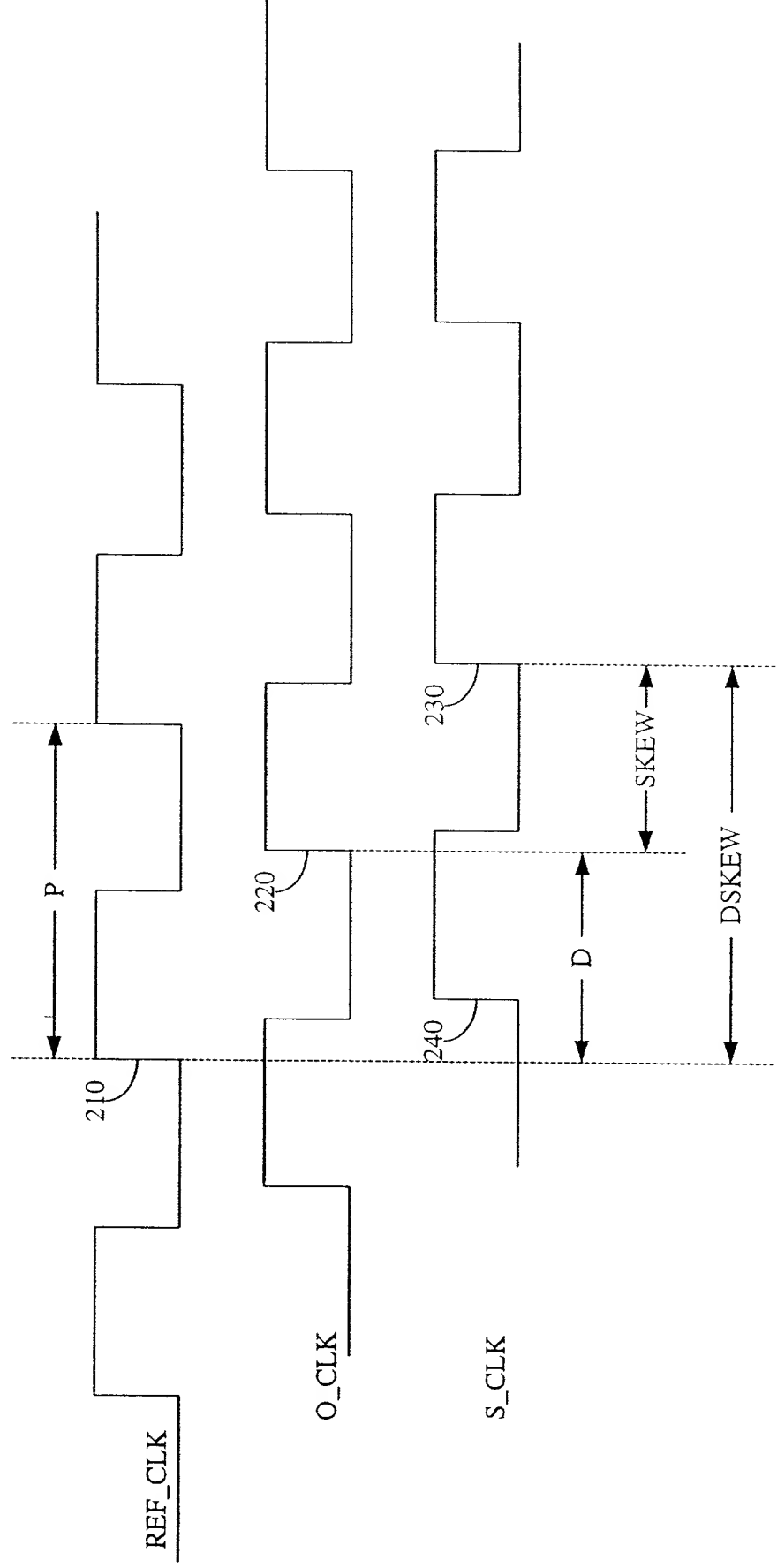


FIGURE 2C

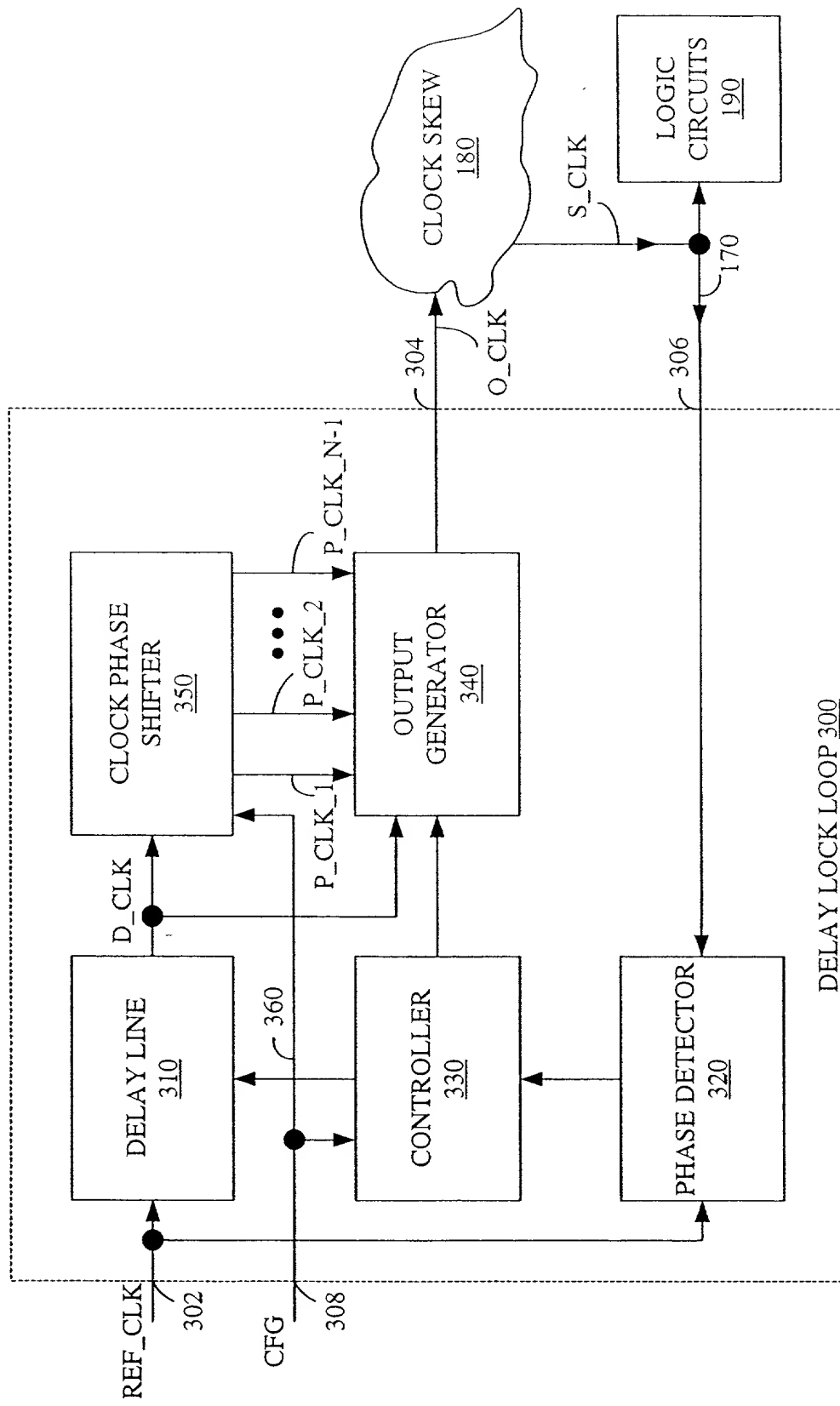


FIGURE 3

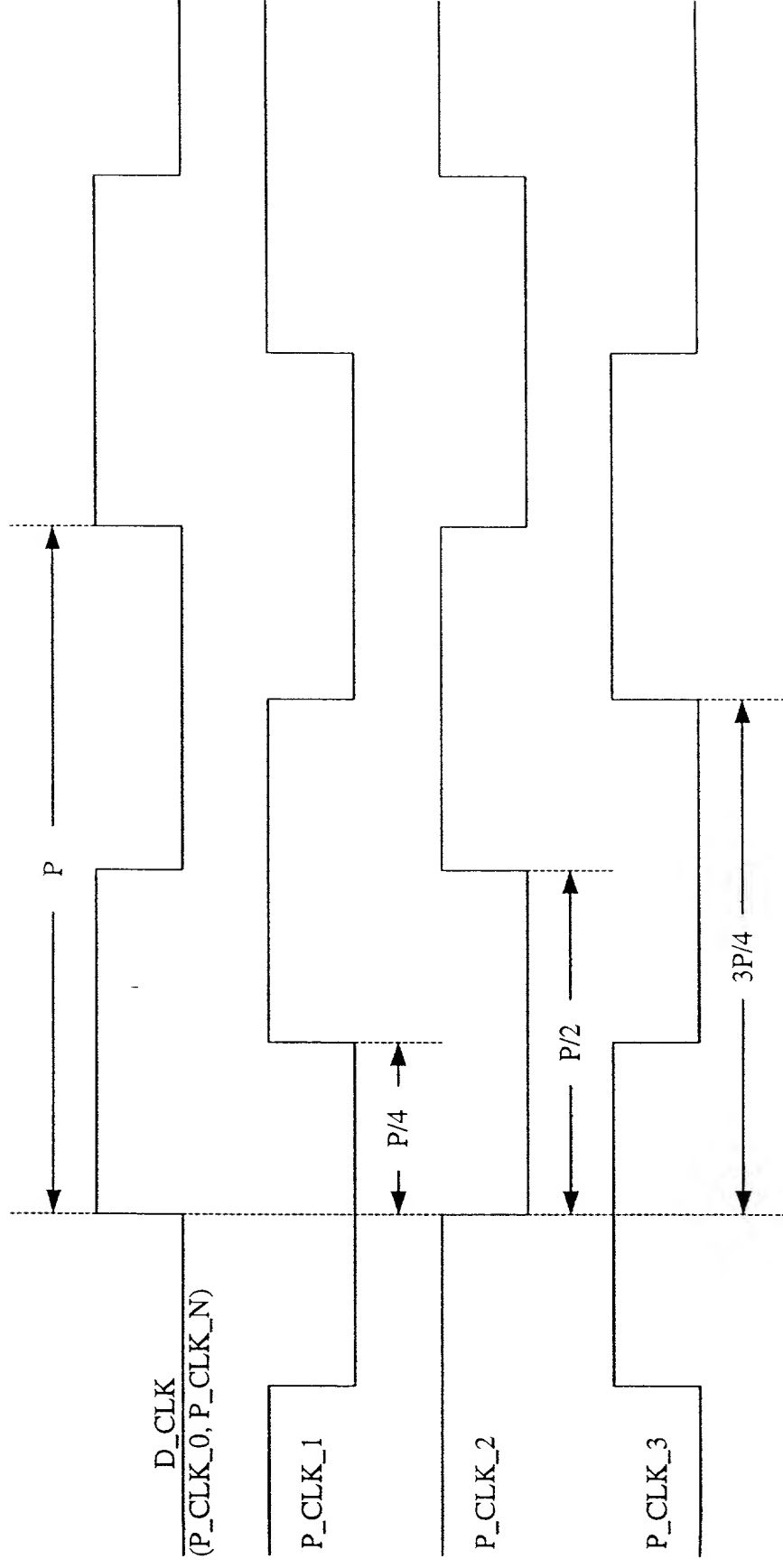


FIGURE 4

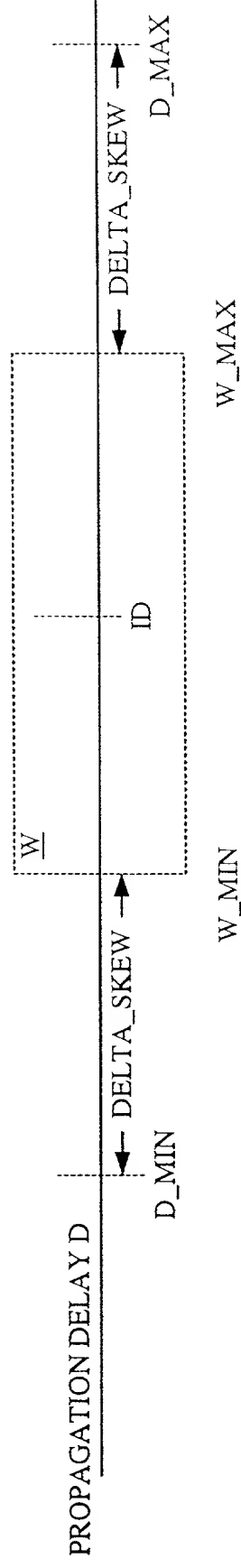


FIGURE 5

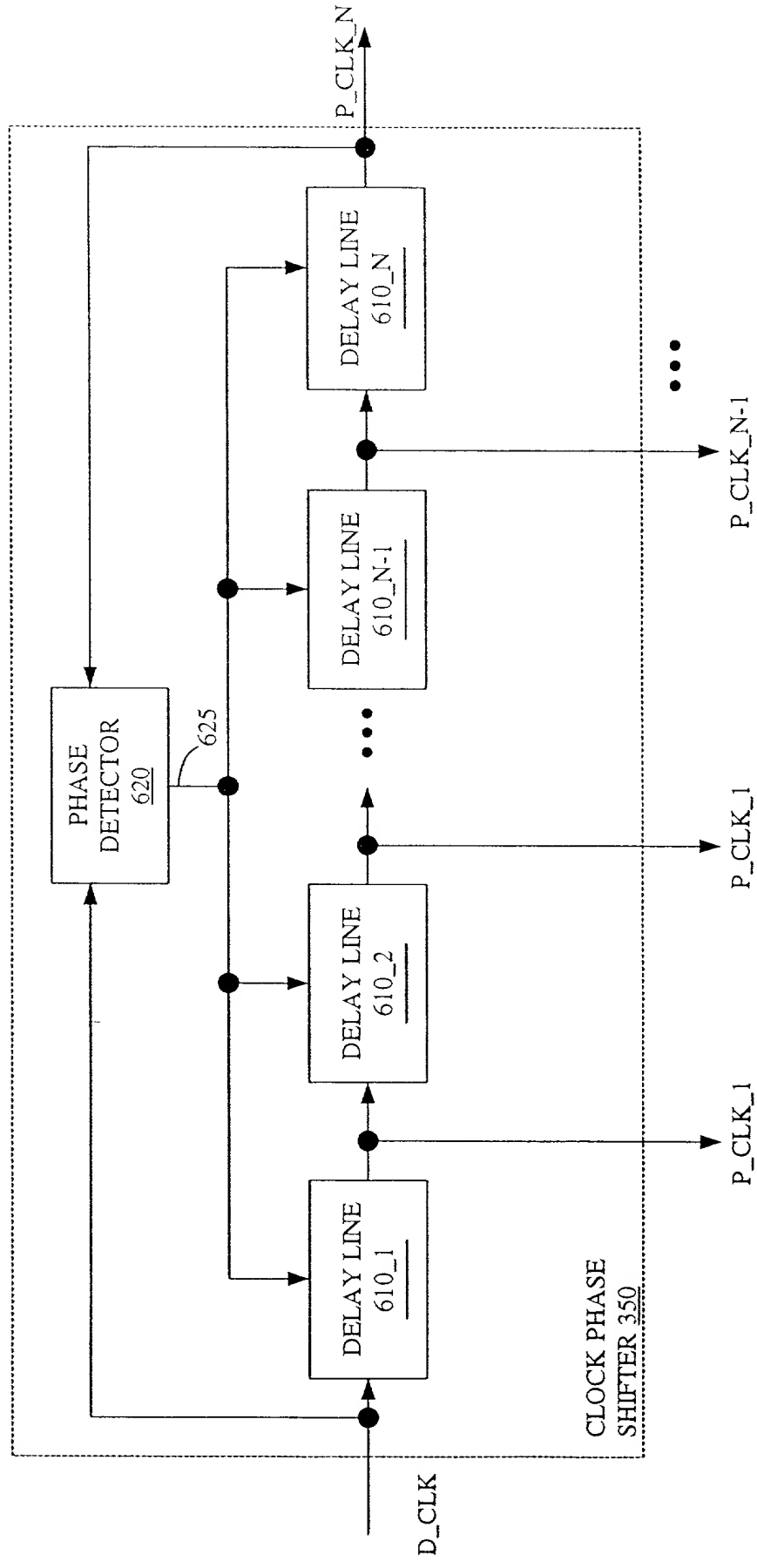


FIGURE 6

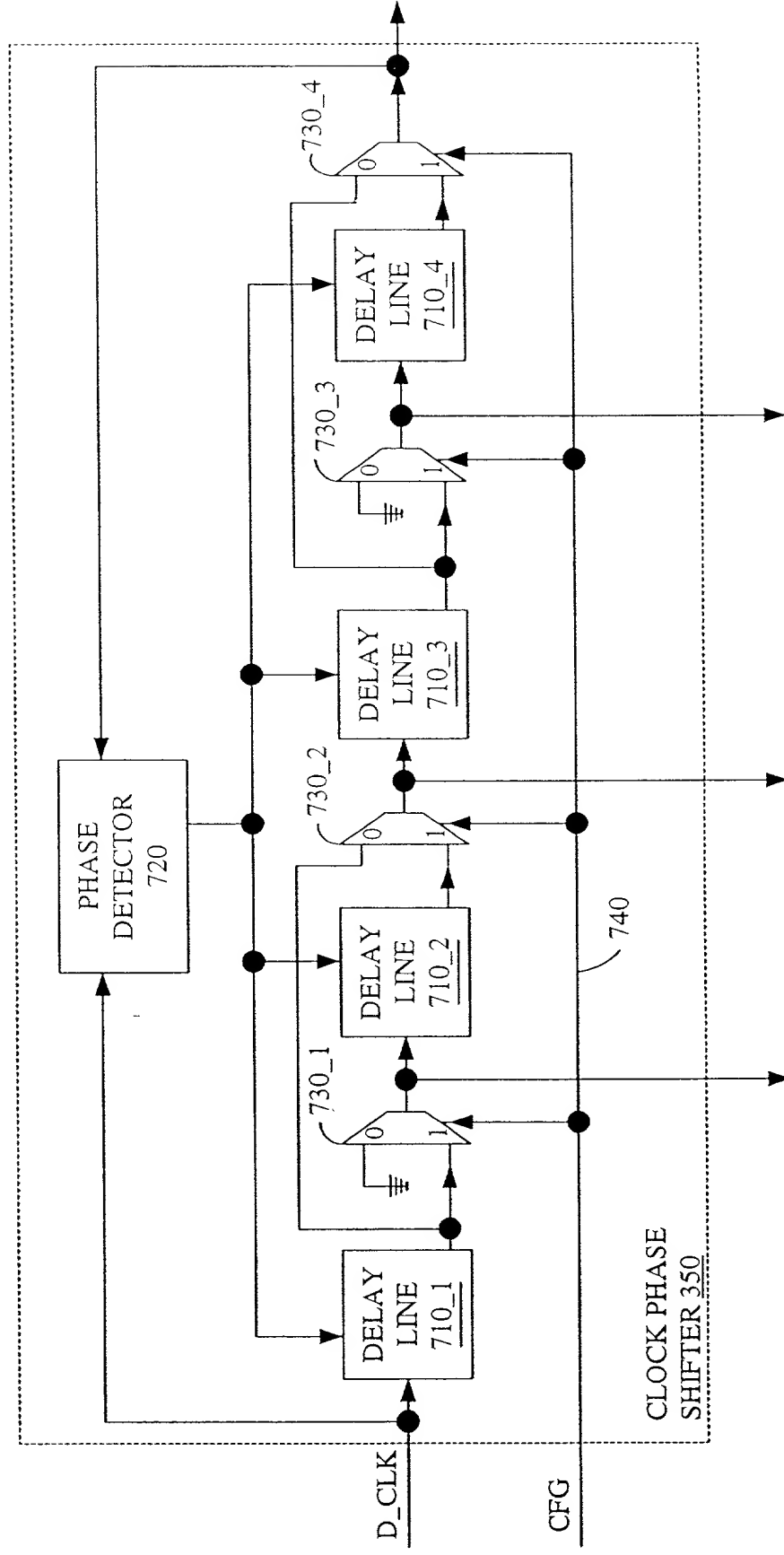


FIGURE 7

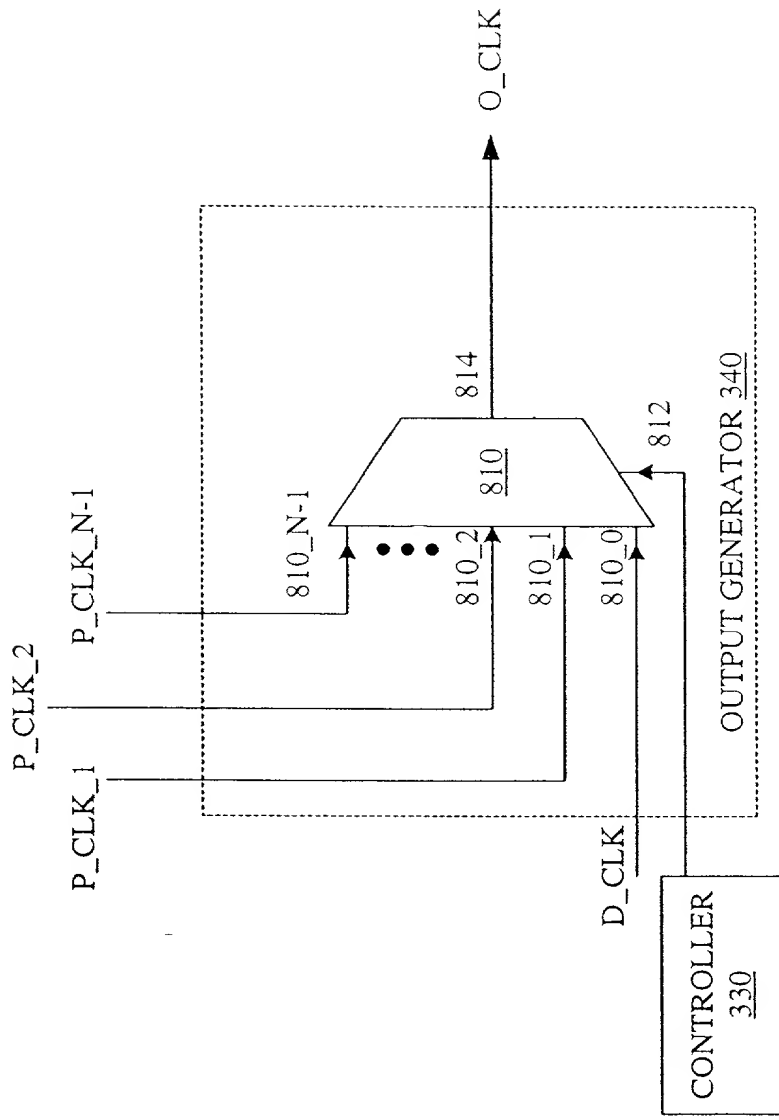


FIGURE 8

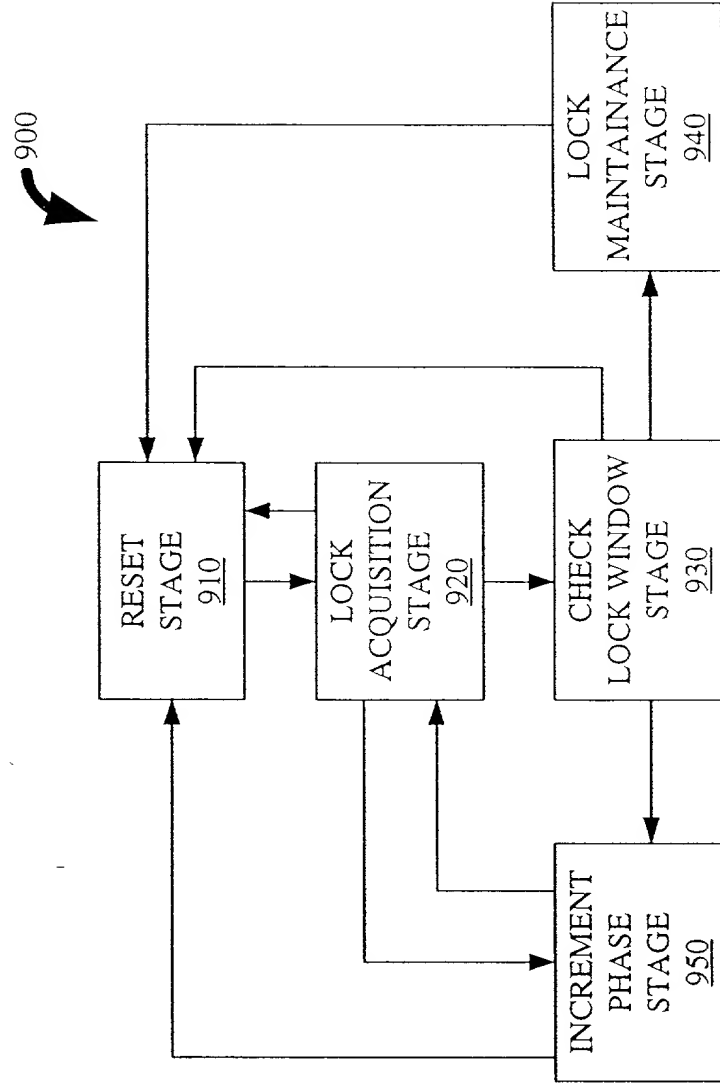


FIGURE 9

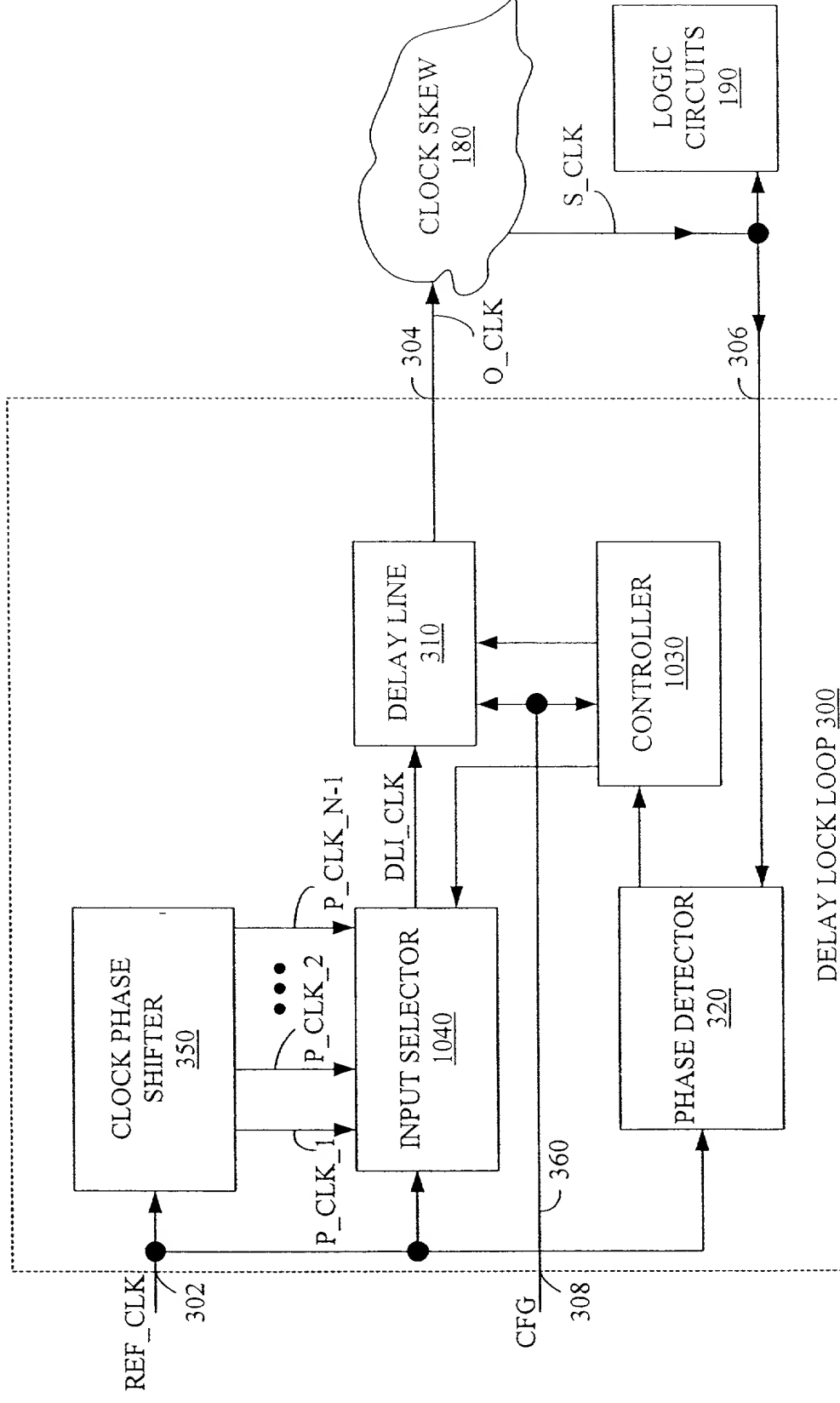


FIGURE 10

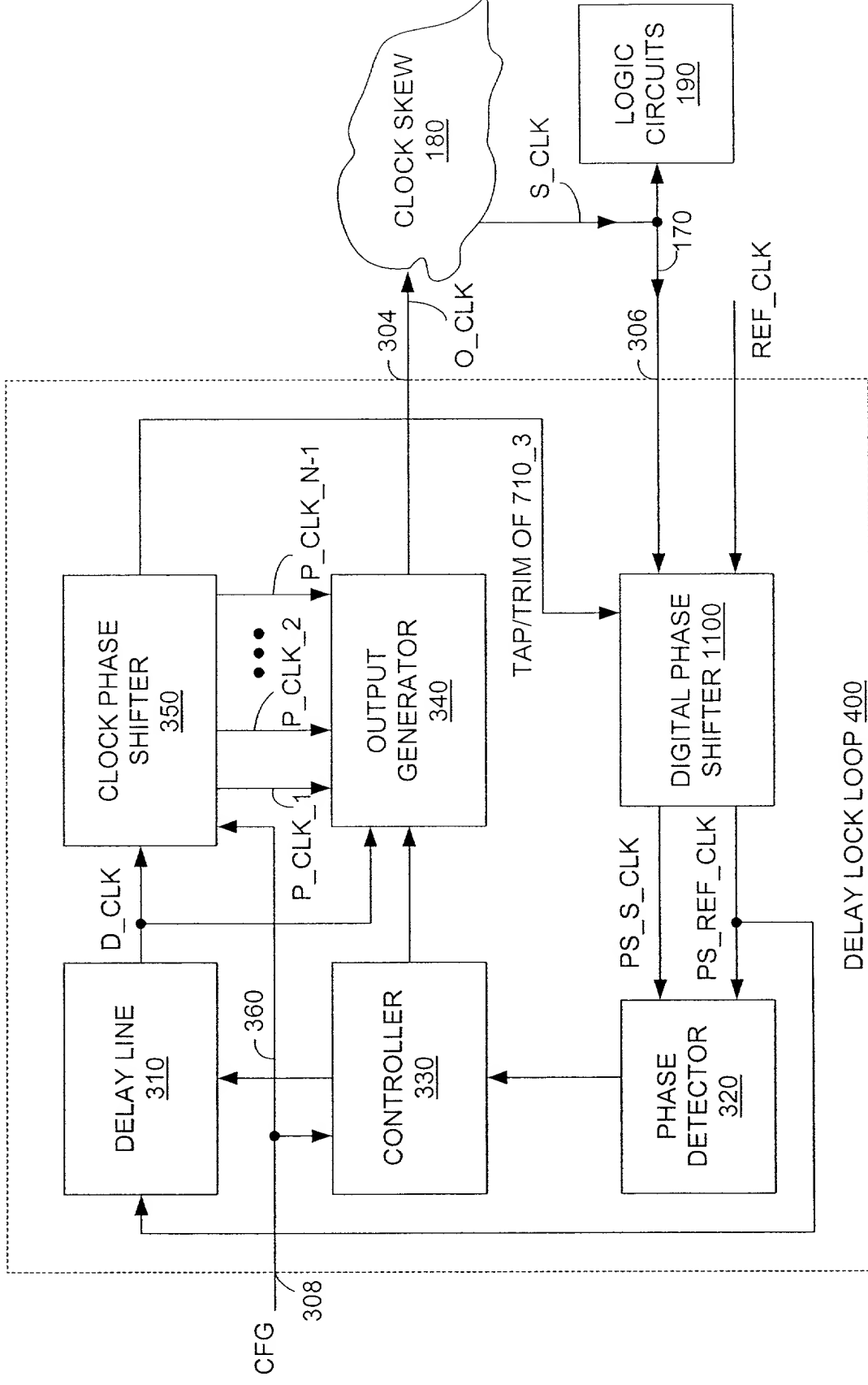


FIGURE 11



FIG. 12

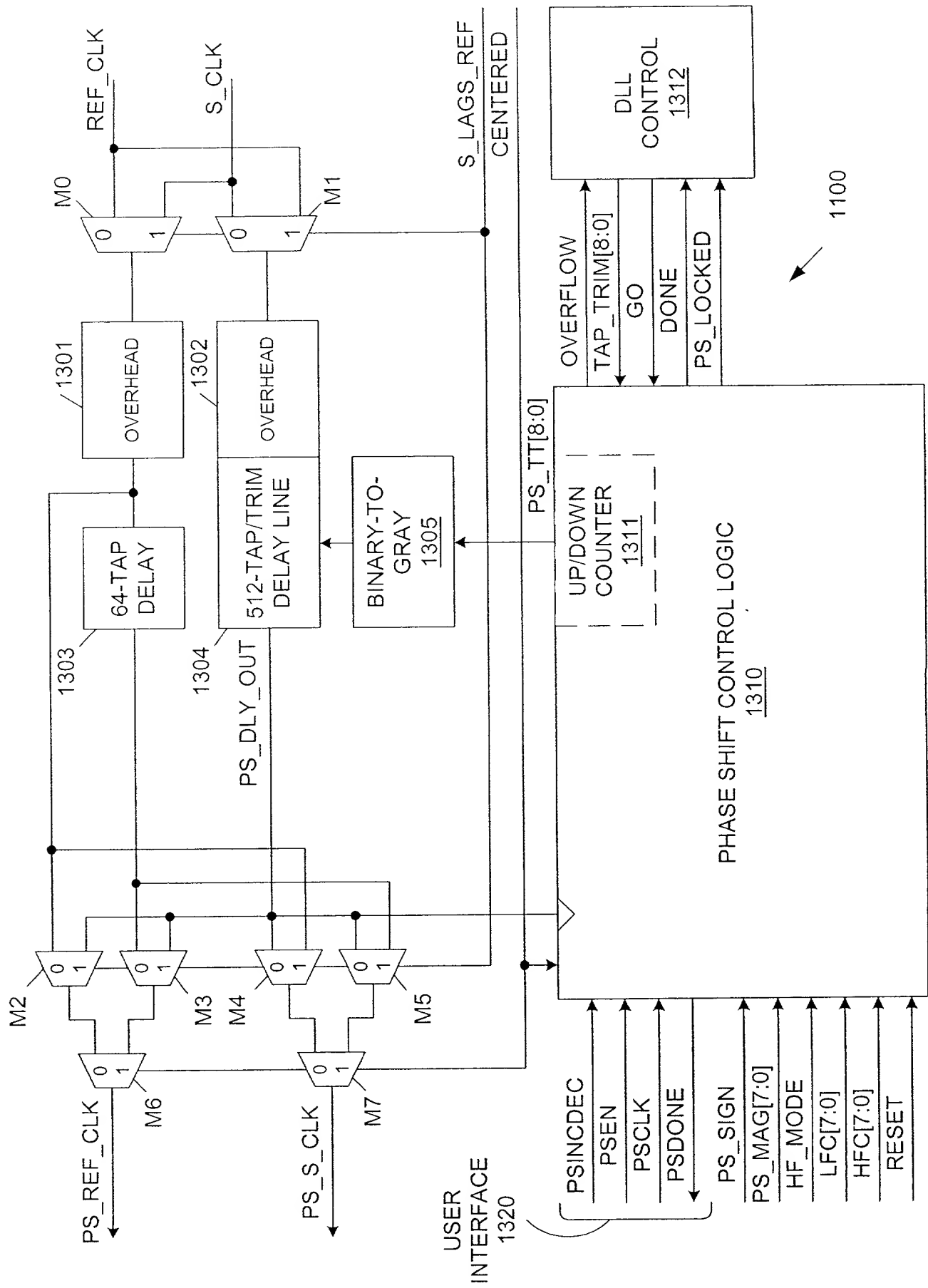


FIG. 13

S_LAGS_REF = 0
CENTERED = 0

FIRST FIXED
MODE

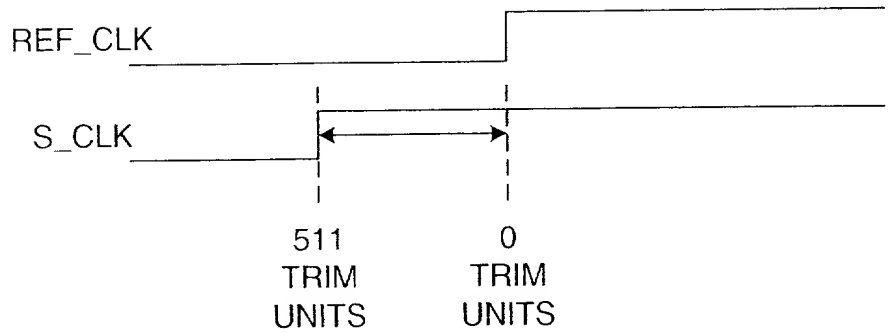


FIG. 14A

S_LAGS_REF = 1
CENTERED = 0

SECOND FIXED
MODE

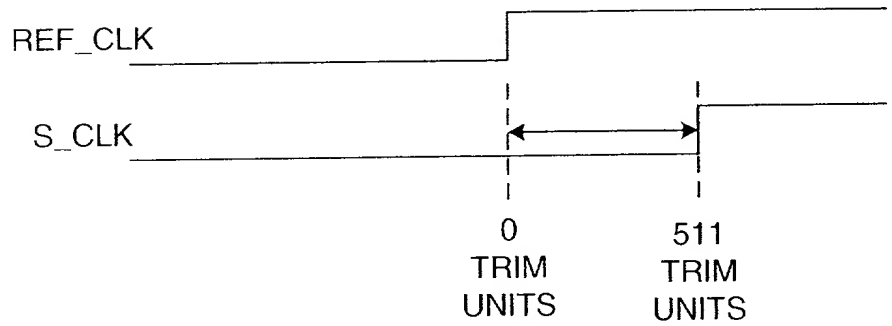


FIG. 14B

S_LAGS_REF =
0 or 1
CENTERED = 1

FIRST AND SECOND
VARIABLE MODES

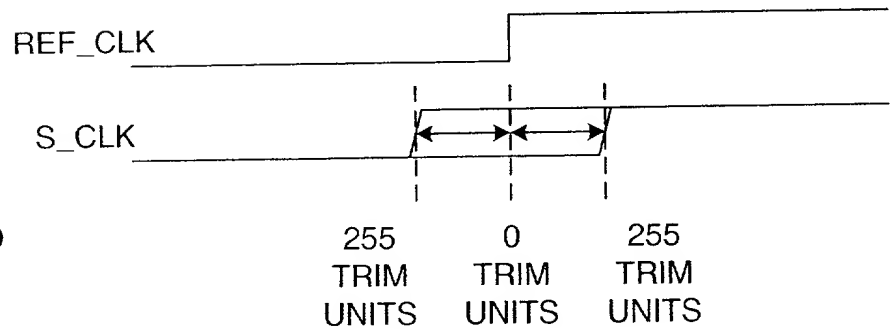


FIG. 14C

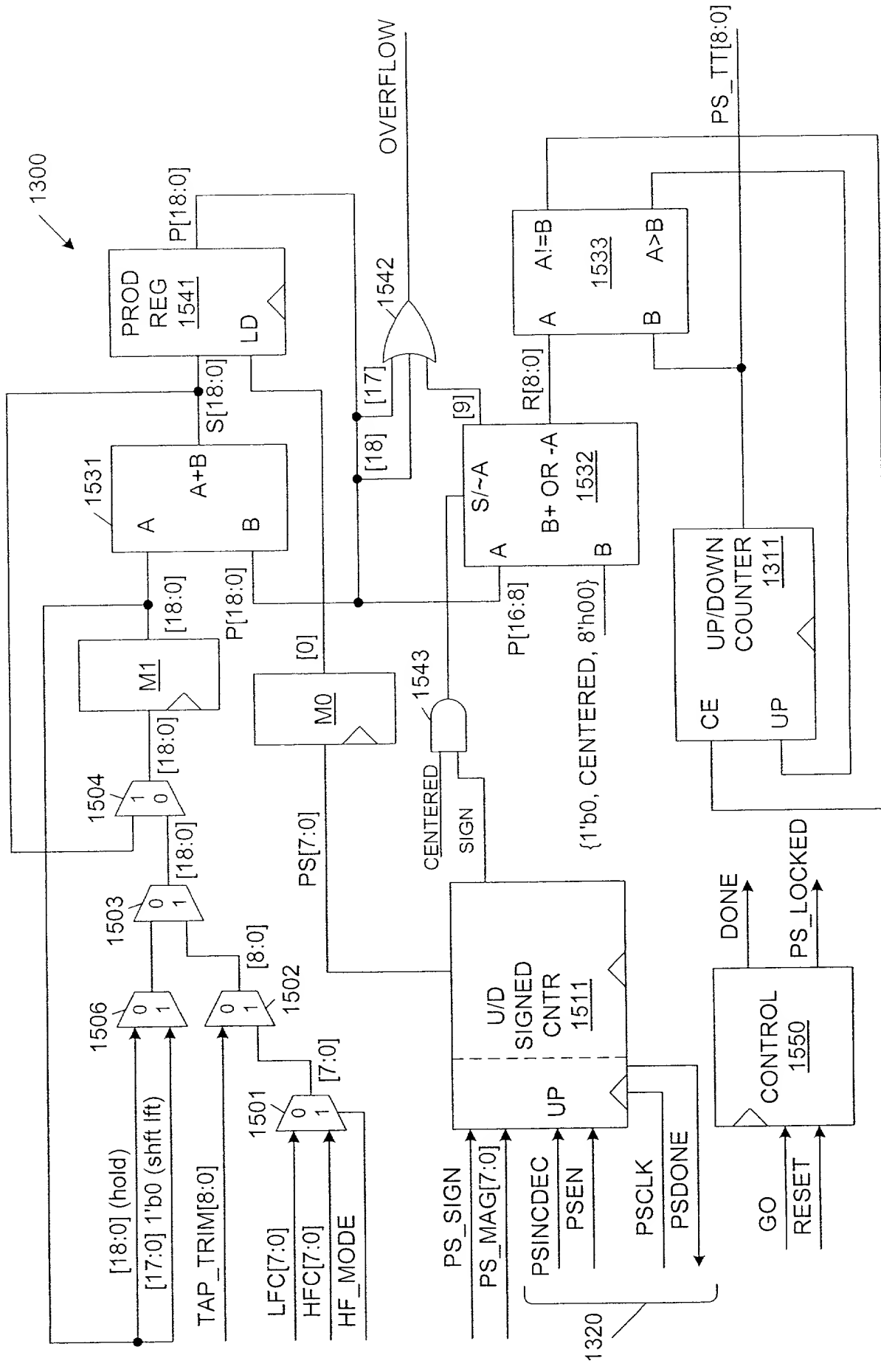


FIG. 15

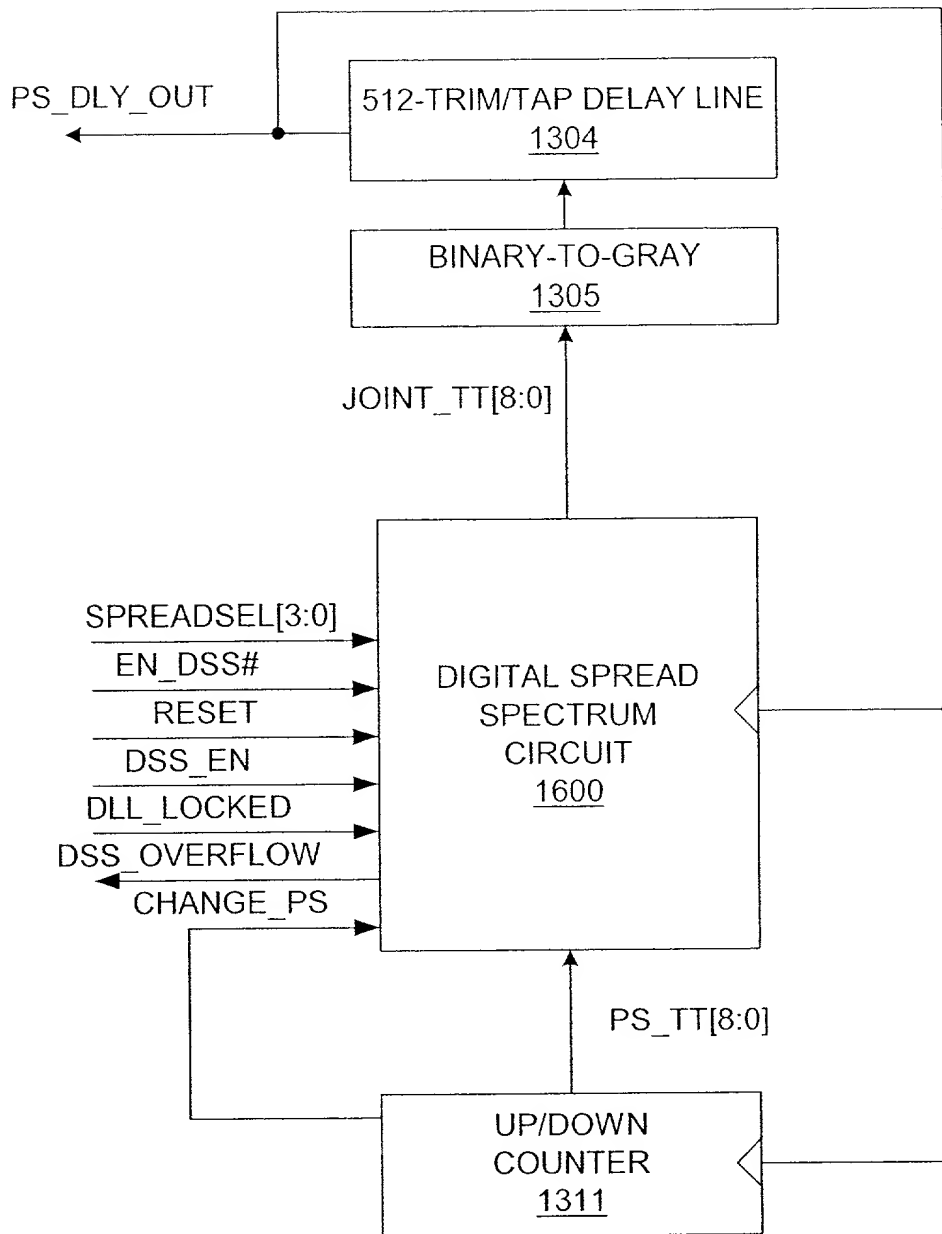


FIG. 16

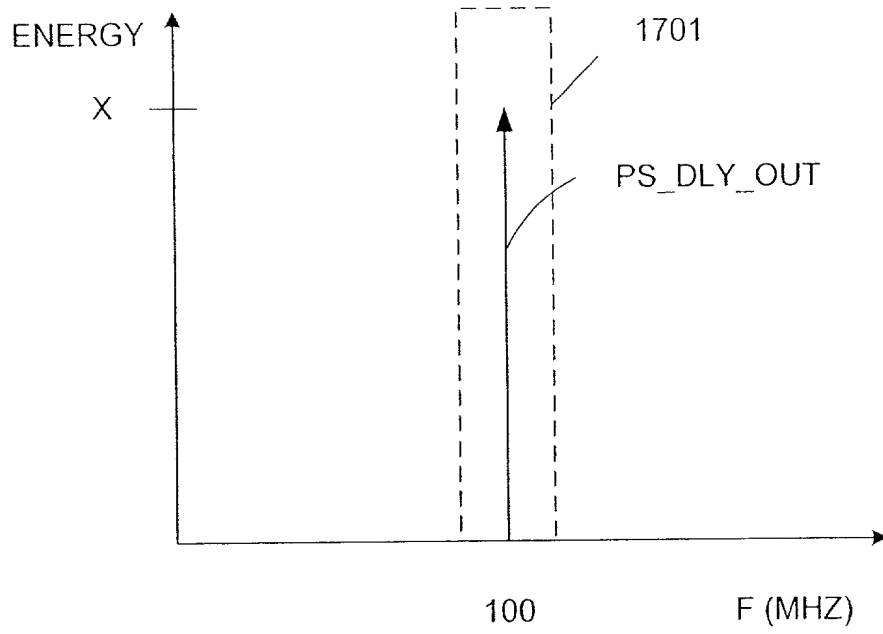


FIG. 17A

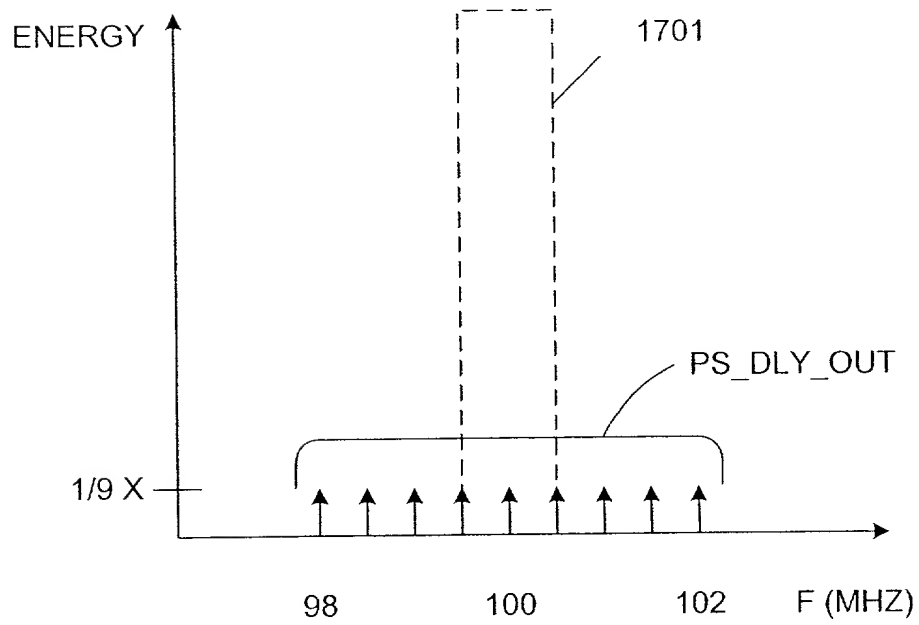


FIG. 17B

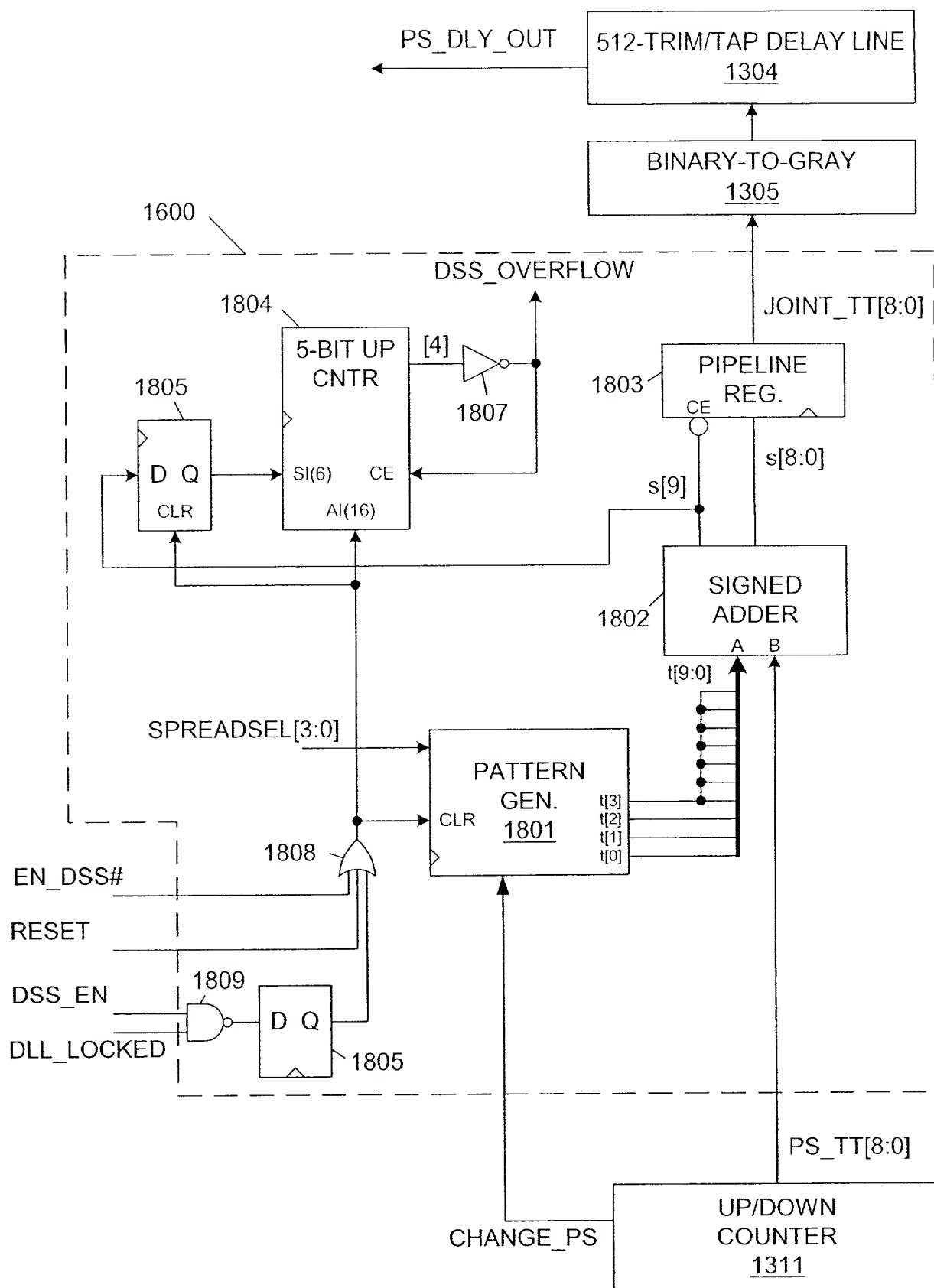


FIG. 18

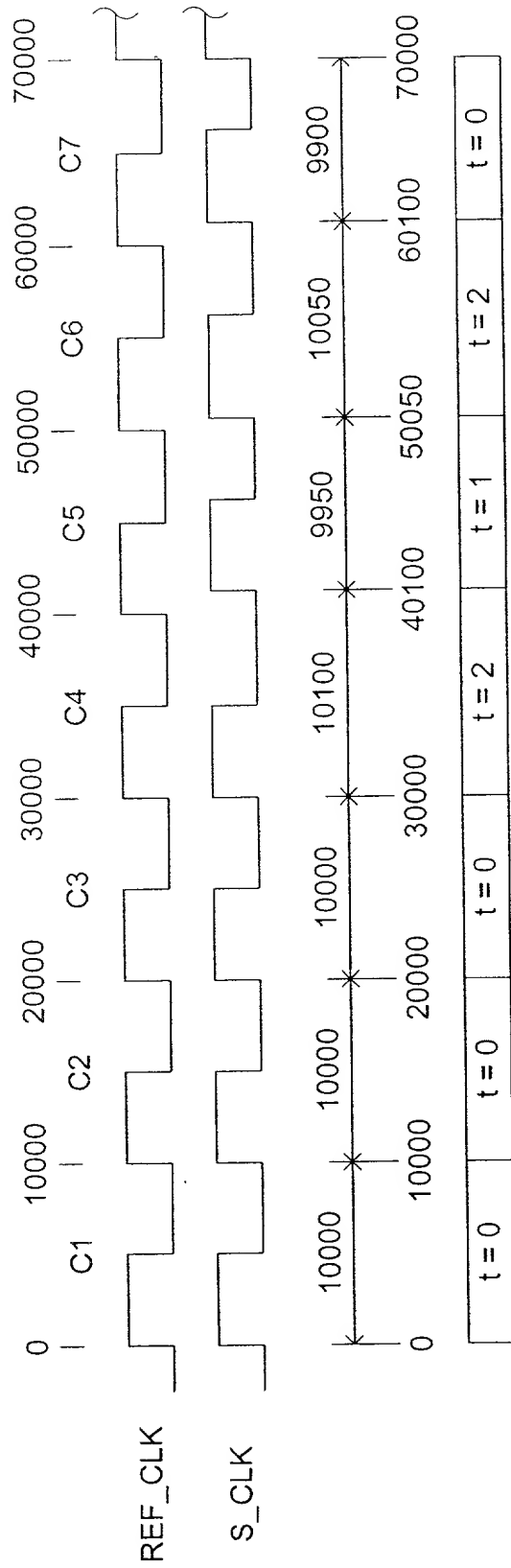


FIG. 19A

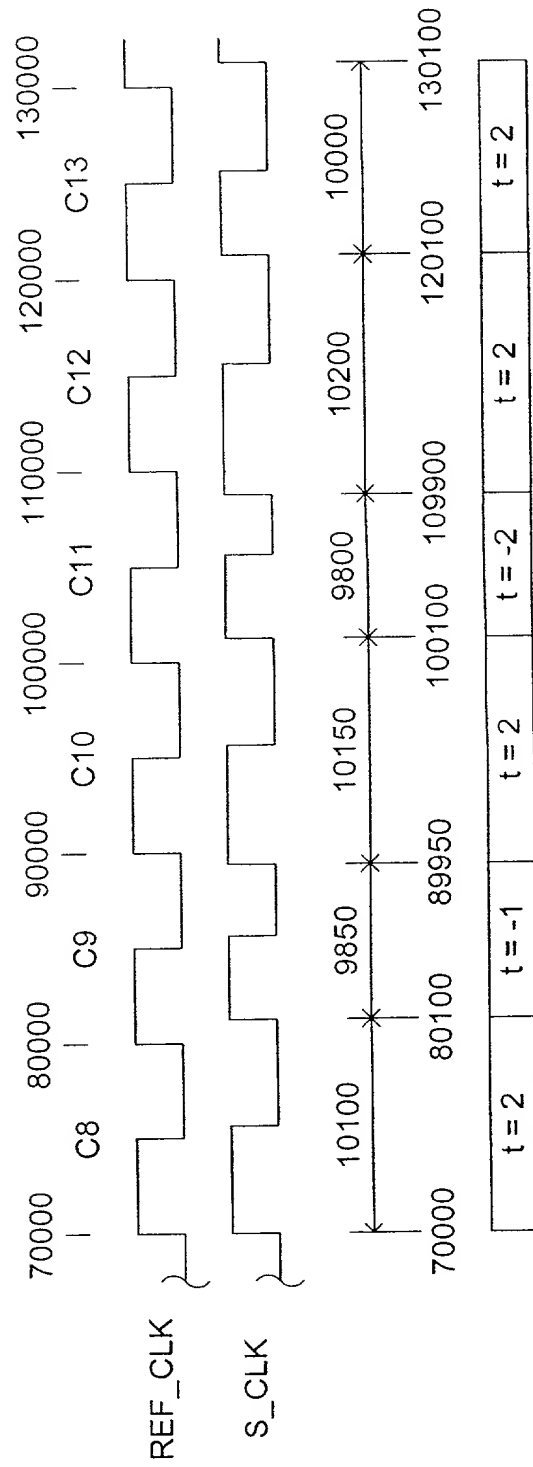


FIG. 19B

DECLARATION FOR PATENT APPLICATION

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below adjacent to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of subject matter (process, machine, manufacture, or composition of matter, or an improvement thereof) that is disclosed and/or claimed and for which a patent is solicited by way of the application entitled

DIGITAL SPREAD SPECTRUM CIRCUITRY

which (check)

- ☒ is attached hereto.
☐ and is amended by the Preliminary Amendment attached hereto.
☐ was filed on _____ as Application Serial No. _____.
☐ and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified application, including the claims, including portions amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, § 1.56(a).

I hereby claim foreign priority benefits under title 35, United States Code, § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)	Priority Claimed	
	Yes	No
_____ (Number) (Country) (Day/Month/Year Filed)		
_____ (Number) (Country) (Day/Month/Year Filed)	Yes	No

I hereby claim the benefit under 35 U.S.C. § 119(e) of any United States provisional application(s) listed below

_____ (Application Number(s))	_____ (Filing Date (MM/DD/YYYY))
----------------------------------	-------------------------------------

I hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) listed below and, insofar as any subject matter of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, § 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, § 1.56(a) which occurred between the filing date of the prior application(s) and the national or PCT international filing date of this application:

09/102,740	June 22, 1998	Pending
(Application Serial No.)	(Filing Date)	(Status-patented, pending, abandoned)

_____ (Application Serial No.)	_____ (Filing Date)	_____ (Status-patented, pending, abandoned)
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_____ (Application Serial No.)	_____ (Filing Date)	_____ (Status-patented, pending, abandoned)
-----------------------------------	------------------------	--

I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and to transact all business in the United States Patent and Trademark Office connected herewith:

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Patrick T. Bever (33,834); E. Eric Hoffman, (38,186); Edward S. Mao (40,713); Julie Stephenson (41,330); and Jeanette S. Harms (35,537) all located at Bever Hoffman & Harms, LLP, 2099 Gateway Place, Suite 320, San Jose, California 95110.

Address all telephone calls to: Edel M. Young at Telephone No. (408) 879-4969

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Title 18, United States Code, § 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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